

CHAPTER 5

SYNTHETIC APERTURE RADAR (SAR) DATA PROCESSING

Active Microwave Users Working Group

SAR Data Processing Panel:

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INTRODUCTION

The SAR Data Processing Panel met to "identify the available and optimal methods for generating SAR imagery for NASA applications." Because this panel was the first NASA-sponsored workshop panel to address the SAR-data-processing problem specifically, it was decided that the panel should cover this subject in a broad manner, by (1) starting with the known applications for SAR imagery, (2) identifying the SAR image quality and data-processing requirements associated with these applications, (3) defining the mathematical operations and algorithms required to process sensor data into SAR imagery, (4) discussing the architecture of dedicated SAR image formation processors, and (5) addressing the technology necessary to implement the SAR data processors used in both general purpose and dedicated imaging systems.

To focus the panel's work, a list of 21 questions divided into the categories of (1) Applications and Requirements, (2) Algorithms and Architecture, and (3) Implementation Technology was provided the participants. Each panel member was provided with copies of pertinent documents (refs. 5-1 to 5-4). Additional reference documentation was available as described in the bibliography at the end of this chapter. Presentations were made to the panel as a whole by Mr. R. Jordan of the JPL, who discussed the Seasat SAR and its associated data processing; by Mr. B. Manning of the Goodyear Aerospace Corporation, who described the digital SAR data processors built by Goodyear for military applications; by Dr. R. Thoene of the Hughes Aircraft Company, who discussed the Hughes programmable signal processor (PSP) approach to SAR data processing; and by Dr. R. K. Moore of the University of Kansas, who discussed the scanning synthetic aperture radar (scansar) concept and a number of different techniques for SAR data processing.

After these general presentations, the panel was divided into three subpanels to address the three major categories of questions. These subpanels were constituted as follows.

Subpanel A, Applications and Requirements

R. K. Moore, chairman
H. A. Ahr
R. E. Harrison
R. C. Webber

Subpanel B, Algorithms and Architecture

S. Francisco, chairman
D. A. Ausherman
R. L. Jordan
R. Thoene

Subpanel C, Implementation Technology

B. Manning, chairman
L. J. Cutrona
J. S. Heuser
J. Justus

These subpanels discussed and wrote responses to their assigned questions. These written responses were supplied to all the panel members for comment and review.

After the written responses to the questions were reviewed, the panel was assembled as a whole and a list of recommendations was drawn up. Finally, the individual panel members were polled to compile a list of the important conclusions drawn from the workshop.

ORBITAL SYNTHETIC APERTURE RADAR (SAR) SENSING

An important objective of the NASA microwave-remote-sensing program is to provide a readily accessible source of remotely sensed data for Federal, State, and private agencies in a form that will provide accurate and timely information on which to base policy and planning decisions. A major component of the microwave-remote-sensing program is, and will continue to be, synthetic aperture imaging radar systems.

The economic benefits from the uses of optical imagery obtained from Earth-orbiting satellites are well known. Active microwave imagery with resolution better than that of optical imagery and with coverage matching that of optical imagery can be obtained by using the SAR on orbiting platforms. It is reasonable to expect substantial additional economic benefits from the use of active microwave imagery to supplement and complement optical imagery. For these benefits to be fully realized, it will be necessary for NASA to provide users with active microwave imagery in the same way that optical imagery is presently provided.

Because of the complexity of the SAR-data-processing problem, users cannot be expected to perform the processing required to form SAR images from raw sensor data. Thus, NASA must pursue the development of appropriate SAR-data-processing capabilities.

It is recognized that two distinct types of processing requirements must be addressed: those requirements that apply to systems designed to support a broad range of applications - in a manner not unlike that of the present Landsat program - and those requirements that apply to dedicated systems such as might be implemented to monitor soil moisture or sea ice conditions. For the case of satellites that support a number of different user applications, the scope of the data-processing problem (i.e., the diverse applications requirements, the wide range of engineering trade-offs and system implementation options, and the sheer volume of data that could be accumulated) is such that the required processing capability can best be addressed by a highly flexible and complex centralized-data-processing facility. For dedicated systems, onboard processing appears to be an attractive alternative. This alternative will become an increasingly viable option as the technologies of small, low-power processing modules (e.g., charge-coupled devices (CCD's)) mature.

A program for development of (1) imaging radar systems for space use and (2) the associated processors must be viewed as part of a long-term development to a full operational capability at some date rather far in the future. If this view is taken, the various components of the program can follow logically and the required capabilities will be ready for use when the uses are authorized.

One can envision an ultimate system in which the constituents of a family of Earth observation spacecraft are simultaneously in orbit, providing different services. Such a family will include special-purpose spacecraft for particular applications (such as water resources or geology), special-purpose spacecraft for performing particular measurements of value in many applications (such as soil moisture), and large, general-purpose spacecraft systems capable of providing high-quality image information for a wide variety of users. Although the spacecraft considered here will all carry radar systems, many of them (if not all) will also carry other sensors so that the complementary nature of microwave and visible-IR sensors can be exploited for maximum user benefit.

Some of these radars will provide large quantities of data for which sophisticated processing in a central data facility will be required. Other radars will provide smaller quantities of data for specialized purposes, with immediate use thereof required; these sensors will undoubtedly process the data to image form on board and be capable of being interrogated by telemetry readout stations under the control of widely dispersed users, in the mode of the automatic picture transmission (APT) system with meteorological satellites. The central facility will produce several kinds of products tailored to the needs of different classes of user; some of these products may be planimetric images, but others will almost certainly be feature maps at scales commensurate with other types of maps in the hands of the users. The central facility products will also be available to users throughout the world by means of telecommunications

facilities enabling readout of images or maps direct from the central computer to displays or computers at the user facilities.

Before such a status of operational capability is reached, various intermediate stages will be involved. The first of these stages is about to start with the advent of the imaging radar on Seasat, which will undoubtedly be representative of a class of modest-capability imaging radar systems on satellites, most of which will also carry other sensors and all of which will be dedicated primarily to easily identifiable special uses.

Simultaneous with the development of these systems will be the development and testing of radar systems with use of the Shuttle platform. The Shuttle can be used for radars that will enable the testing of user applications but that also will enable the testing of numerous alternative processing systems and radar configurations, both for future use on large spacecraft and for use on smaller, dedicated free-flying spacecraft.

The early dedicated small spacecraft will probably employ ground processing. Somewhat later, the alternative of onboard processing will be used, but with telemetry to central processing facilities. This system will no doubt be followed soon by an APT capability. The Shuttle test bed will enable the checking out of onboard processing systems; but more than that, it will enable the production of more complex (finer resolution, more frequencies, more polarizations) data, which will facilitate development of the ground-based central processing facility capability to that needed for operational systems. Also, the availability of these more complex processed images will enable use of the central facility for experiments in developing the various kinds of user-desired products.

Before spacecraft systems can become operational, research and development is needed in several areas - not so much to provide inputs to the design of the first radars, because the capability exists now to build them, but rather to prepare for the future experiments to be conducted on the Shuttle and for the future specialized free-flyer radars.

Such research is urgently needed to establish the true needs of the user community. Actual needs for resolution, for example, have a major impact on the complexity of processors; if a special application is to be addressed either with a Shuttle test or with a dedicated free-flyer, the true needs in resolution, gray-level rendition, swath width, frequency of or timeliness of coverage, and radar system parameters must be known to enable design of the simplest system that will meet the user needs. Studies and preliminary development need to be conducted on a wide variety of processing techniques, especially for onboard processor systems.

The number of ways in which SAR signals can be processed into images is large, and several of the possible techniques have not been tested. The trade-offs between these new techniques and the traditional ones must be evaluated. As the electronic art progresses, the optimum solutions to the processor design problem will change; and an ongoing effort in designing alternative processors is needed if decisions to use workable but obsolete techniques are to be avoided at the time hardware decisions are made for the space systems.

Although radar systems themselves are not part of the work of this panel, it is noted that similar studies should be ongoing with regard to the radars that feed into the processor. Not only will this effort enable appropriate components to be available so that the optimum, rather than available, systems can be built, but many radar system decisions also affect processor decisions and the radar studies are an important component of the inputs to the processor studies.

For numerous applications of radar, the combining of images from multiple passes of the radar will be required, as well as the combining of radar images with MSS images, maps, and photographs. Research into the kinds of processing that will be needed to convert the raw radar images into products suitable for such combinations is essential and needed soon. If possible, the results should be tested by using both aircraft-radar and early-space-radar images. In turn, as the space radars become more sophisticated and the number of proven uses increases, such research should continue.

APPLICATIONS AND REQUIREMENTS

The Applications and Requirements Subpanel was supplied with the following questions/instructions to guide its work.

1. What are the applications for SAR imagery? Identify the expected users.
2. What are the SAR image requirements for these applications? Define the requirements in terms of image quality, coverage, and timeliness.
3. How is SAR image quality best defined?
4. What data formats are preferred by the users?
5. What auxiliary information is required by the users?
6. What aircraft experiments should be considered to enable optimization of processing options such as number of looks, quantization level, etc., as a function of application?
7. What data indexing and editing capabilities should the ground data-processing station have?
8. What image registration accuracy should be specified to enable matching radar imagery to that of other image sources?

Radar, Image, and Mission Parameter Requirements

The applications for SAR imagery are described in detail in chapter 2 of this report and in the Active Microwave Workshop Report (ref. 5-1). Of most importance in SAR data processing are the sensor, image, and mission parameters required for the different applications. Different applications

call for different radar, image, and mission parameters. These requirements have been summarized in tables 5-1 to 5-3; the particular requirements for each application are given. Many of the requirements cannot be fully specified at this time because of lack of information on either the character of the radar return or the needs for specific applications, and this deficiency has been indicated in the tables.

The tables have been subdivided into three categories: radar, image quality, and data repetition and timing requirements. Resolution is often considered to be a radar parameter, but in the synthetic aperture system, processing in different ways can give different resolutions; hence, it has been listed in the image quality category.

The incidence angle is defined as the angle between the ray from the radar to the target and the local vertical at the target. For some applications, measurements at specific incidence angles are needed; but most applications can be accommodated with measurements made within rather wide ranges of incidence angle. When the table specifies a wide range, the implication is that any angle within this range will suffice.

In a few cases, the best single frequency for performing a particular task is known; but in most cases, insufficient information is available to enable specifying such a frequency. The frequencies are known for cases wherein microwave spectrometer measurements have been made (primarily those associated with soil moisture and vegetation). In other cases, the primary quantity required is shape and contrast information and the frequency is essentially immaterial. The tables contain examples of all three cases.

For some applications (but not for most), the use of multiple frequencies is required for performing classification tasks or profiling. The column on needed multiple frequencies has examples both of cases wherein the multiple frequencies are actually required and those wherein they are desirable. Only in a few cases is it possible to specify exactly what frequencies are needed, even when it is known that multiple frequencies are either needed or desirable.

Polarization is an important discrimination factor available to the radar interpreter; yet for many applications, only a single polarization is needed and often the particular one used is unimportant. Only in a few cases has it been possible or necessary to identify a particular required like polarization; and for most of the applications wherein multiple polarizations are required, either vertical or horizontal polarization and one of the cross-polarized components are needed.

Image quality depends on a variety of factors, but probably the most important ones are the resolution and the amount of coherent speckle in the image caused by fading of the received signal. Coherent speckle is a fundamental characteristic of monochromatic radar images. It may be significantly reduced by incoherently averaging several independent "looks" at a given scene or by other methods that are equivalent to such averaging.

A recent study has shown how the combined effects of pixel size, shape, and speckle can be treated together and trade-offs made between

TABLE 5-1.- RADAR PARAMETER REQUIREMENTS

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Geology and mineral resources applications				
Structure	≈45 in mountains; near grazing in flat areas	Not important; lower better for vegetation penetration	Ku-band to show structural evidence in vegetation and L-band to penetrate vegetation	Like and cross, VV or HH
Lithology	10 to 20, and anywhere in the 20 to 70 range	Unknown; lower better for vegetation penetration	Unknown, but multiple frequencies are desirable	Like and cross, VV or HH
Construction materials	10 to 20, and anywhere in the 20 to 70 range	Unknown; lower better for vegetation penetration	Unknown, but multiple frequencies are desirable	Like and cross, VV or HH
Route and dam location	≈45 in mountains; near grazing in flat areas	Unknown; lower better for vegetation penetration	A high frequency and a low frequency are desirable	Like and cross, VV or HH
Oceanic applications				
Waves	>20	TBD	TBD	TBD
Sea ice				
Navigation	>20	X- to Ku-band	TBD	Cross
Mapping	>20	X- to Ku-band	TBD	Cross
Icebergs	>50	TBD	TBD	Multiple
Ships and fishing boats	>50	None	None	Single
Pollution	25 + 70	>5 GHz	TBD	Multiple
Coastal changes	>5	None	TBD	Multiple, linear and circular
Kelp monitoring	>30	>12 GHz	None	Multiple
Hurricanes	>10	<3 GHz	TBD	Multiple
Currents	>20	TBD	TBD	Multiple

TABLE 5-1.- Continued

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Cartography and land-use applications				
Urban changes	20 to 70	Probably none - TBD	Not likely	Like and cross
Transportation Routes	20 to 70	Probably none - TBD	No	Like and cross
Traffic	50 to 80	Probably none - TBD	No	Like and cross
Remote area topography	30 to 80	Probably none - TBD	No	Like
Land use				
Suburban	20 to 80	> 8 GHz	Yes - TBD	Like and cross
Rural	20 to 80	> 8 GHz	Yes - TBD	Like and cross
Agriculture and natural vegetation applications				
Crop identification	30 to 70	14 GHz	Yes - 9, 14, and 17 GHz	Like and cross
Crop and pasture condition				
State of growth	30 to 70	> 8 GHz	Yes - TBD	Single
Stress, disease	30 to 70	> 8 GHz	Yes - TBD	Single
Soil moisture	5 to 20	4 to 5 GHz	Probably not - TBD	Single
Field boundaries	30 to 70	> 8 GHz	Probably not - TBD	Like and cross
Farming practices	30 to 80	Probably none - TBD	Probably not - TBD	Like and cross
Natural vegetation	30 to 70	> 8 GHz	Yes - TBD	Like and cross
Forest community				
Identification	20 to 70	TBD	Yes - TBD	Like and cross
Status	20 to 70	TBD	Yes - TBD	Like and cross
Forest burn and harvest	10 to 40	TBD	No	Single
Erosion	30 to 80	Probably none - TBD	No	Single
Irrigation	5 to 20	4 to 5 GHz	Probably not - TBD	Single

TABLE 5-1.- Concluded

Application	Incidence angle, deg	Best single frequency	Needed multifrequency	Polarization
Water resources applications				
Soil moisture condition	7 to 22	4 to 5 GHz	Probably not - TBD	Single (VV or HH)
Rainfall assessment	7 to 22	4 to 5 GHz	Probably not - TBD	Single
Watershed runoff coefficient	30 to 70	TBD	Probably yes - TBD	Like and cross
Standing water, ponds and lakes	> 30	High better	No	HH and cross
Lake ice	30 to 80	TBD	Possibly desirable - TBD	TBD
Snow cover	25 to 75 (TBD)	TBD	TBD	TBD
Thaw line	22 to 50 (TBD)	TBD	TBD	TBD
Glaciers	TBD	TBD	TBD	TBD
Water pollution	25 to 70	TBD	TBD	VV and cross

TABLE 5-2.- IMAGE PARAMETER REQUIREMENTS

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Geology and mineral resources applications					
Structure	30 to 200	Not important	TBD	15 to 20	No
Lithology	30 to 100	Unknown (1?)	TBD	15 to 20	Probably none
Construction materials	30 to 100	Unknown (1?)	TBD	15 to 20	Probably none
Route and dam location	20 to 50	Unknown; probably none	TBD	15 to 20	Probably none
Oceanic applications					
Waves	<20 to 30	1	TBD	20	Probably image and spectrum
Sea ice					
Navigation	25 to 75	1	TBD	15 to 20	No
Mapping	100	1	TBD	15 to 20	No
Icebergs	1 to 25 - TBD	TBD	TBD	15 to 20	Possibly - TBD
Ships and fishing boats	100 to 400	No requirement	TBD	15 to 20	Possibly - TBD
Pollution	100	2?	TBD	15 to 20	Possibly - TBD
Coastal changes	10 to 50	TBD	TBD	15 to 20	Possibly - TBD
Kelp monitoring	30 to 100	TBD	TBD	15 to 20?	No
Hurricanes	100 to 500	TBD	TBD	20 to 30	Possibly - TBD
Currents	50 to 500	TBD	TBD	15 to 20	Possibly - TBD

TABLE 5-2.- Continued

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Cartography and land-use applications					
Urban changes	5 to 50	3	< 10	30	Yes
Transportation					
Routes	10 to 50	2	< 10	30	Yes
Traffic	5 to 15	3	< 10	20	Yes
Remote area topography	25 to 100	3 - TBD	100	20	No
Land use					
Suburban	25 to 100	2	25	20	Possibly - TBD
Rural	25 to 100	2	25	20	Possibly - TBD
Agriculture and natural vegetation applications					
Crop identification	20 to 100	1	50	20	Probably - TBD
Crop and pasture condition					
State of growth	20 to 100	1	50	20	Possibly - TBD
Stress, disease	10 to 100				
Soil moisture	20 to 200	1	50	20	Possibly - TBD
Field boundaries	20 to 100	2	50	20	Possibly - TBD
Farming practices	20 to 100	2 to 3	50	20	Possibly - TBD
Natural vegetation	50 to 200	1	50	20	Possibly - TBD
Forest community					
Identification	3, or 50 to 200	1	100	20	Possibly - TBD
Status	3, or 20 to 50	1	50	20	Possibly - TBD
Forest burn and harvest	20 to 100	3	100	20	Possibly - TBD
Erosion	10 to 50	1 to 2	100	20	No
Irrigation	20 to 100	1	100	20	Possibly - TBD

TABLE 5-2.- Concluded

Application	Equivalent resolution, m	Gray-level precision, dB	Geometric precision, m	Single-product dynamic range, dB	Multiple products
Water resources applications					
Soil moisture condition	20 to 200	1	TBD	20	Possibly - TBD
Rainfall assessment	20 to 200	1	TBD	20	Possibly - TBD
Watershed runoff coefficient	20 to 200	1 - TBD	TBD	20	No
Standing water, ponds and lakes	50	Coarse - TBD	TBD	20	Possibly - TBD
Lake ice	50	1	TBD	20	Yes - map and image
Snow cover	100 to 200	TBD	TBD	20	Possibly - TBD
Thaw line	200	TBD	TBD	20	Possibly - TBD
Glaciers	3 to 100	TBD	TBD	20	TBD
Water pollution	10 to 50	TBD	TBD	30	Probably - TBD

TABLE 5-3.- MISSION PARAMETER REQUIREMENTS

Application	Need for multiple-aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km ²	Extent of coverage, percent
Geology and mineral resources applications							
Structure	At least two at 90°; prefer three at 0°, 90°, and 180°	Winter and summer	None	Months	None	>5 000	100
Lithology	At least two at 90°	Once	In winter	Months	None	> 625	100
Construction materials	At least two at 90°	Winter and summer	At least in winter	2 mo	None	> 625	100
Route and dam location	At least two at 90°	Winter and summer	Depends on project	2 to 3 mo	All	> 625	100
Oceanic applications							
Waves	None	6 to 12 hr	TBD	6 hr	All	400	< 100
Sea ice	None	12 to 48 hr	TBD	6 hr	All	Wide area	100
Navigation	None	Weekly	TBD	5 d	All	Wide area	< 100
Mapping	None						
Icebergs	None	1 to 3 d	Yes	6 hr	TBD	Wide area	100
Ships and fishing boats	None	Daily	Yes	1 d	TBD	Wide area	100 (of selected areas)
Pollution	None	Daily	Yes	2 to 24 hr	TBD	400	100
Coastal changes	None	6 mo	Yes	1 mo	None	1 000	100
Kelp monitoring	None	6 mo	TBD	10 d	TBD	TBD	TBD
Hurricanes	TBD	TBD	Yes	2 hr	All	40 000	100
Currents	TBD	TBD	TBD	5 to 15 d	None	TBD	TBD

TABLE 5-3.- Continued

Application	Need for multiple- aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km ²	Extent of coverage, percent
Cartography and land-use applications							
Urban changes	Yes	30 d	(a)	15 d	Indefinite	10 ⁷	10
Transportation							
Routes	Yes	30 d	(a)	7 d	None	10 ⁷	10
Traffic	Yes	30 d	TBD	7 d	Rush hours	10 ⁷	10
Remote area topography	Yes	Indefinite	(a)	90 d	None	10 ⁷	TBD
Land use							
Suburban	No	6 mo	(a)	30 d	None	10 ⁷	TBD
Rural	Yes	3 mo	(a)	15 d	None	10 ⁷	TBD
Agriculture and natural vegetation applications							
Crop identifi- cation	Probably - TBD	7 d	Yes	2 d	Probably none - TBD	10 ⁷	TBD
Crop and pasture condition							
State of growth	Probably - TBD	7 d	Yes	2 d	Probably none - TBD	10 ⁷	TBD
Stress, disease	Probably not - TBD	7 d	TBD	TBD	Probably none - TBD	10 ⁷	TBD
Soil moisture	Probably - TBD	2 d	Yes - TBD	TBD	Yes - TBD	10 ⁷	TBD
Field boundaries	No	1 yr	Yes	30 d	None	10 ⁷	TBD
Farming practices	Yes	30 d	(a)	2 d	None	10 ⁷	TBD
Natural vegetation	In some areas	7 d	Yes	2 d	Probably none - TBD	10 ⁷	TBD
Forest community identification							
Status	In some areas	1 yr	TBD	30 d	Probably none - TBD	10 ⁷	TBD
	In some areas	1 yr	TBD	30 d	Probably none - TBD	10 ⁷	TBD
Forest burn and harvest	In some areas	7 d	Yes	TBD	None	10 ⁷	TBD

^aNot applicable.

TABLE 5-3.- Concluded

Application	Need for multiple-aspect looks	Frequency of coverage	Timeliness required	Data lag allowed	Time-of-day requirement	Area of coverage, km ²	Extent of coverage, percent
Agriculture and natural vegetation applications (Cont'd.)							
Erosion	In some areas	7 mo	(b)	30 d	None	10 ⁷	TBD
Irrigation	TBD	2 to 10 d	Yes	TBD	None	10 ⁷	TBD
Water resources applications							
Soil moisture condition	No	2 to 10 d	Yes	2 d	Yes - TBD	10 ⁷	25
Rainfall assessment	No	(b)	1 to 3 d after rainfall	2 d	(b)	10 ⁵	100
Watershed runoff coefficient	Two orthogonal	3 mo	(b)	1 mo	(b)	250 000	20
Standing water, ponds and lakes	None	Weekly	Yes	2 d	(b)	10 ⁷	1
Lake ice (not for navigation)	None	Weekly	Yes	2 d	TBD	10 ⁵	20
Snow cover	Two orthogonal	2 to 6 d	Yes	2 d	Yes	10 ⁶	50
Thaw line	None	6 d	Yes	2 d	Yes	10 ⁵	<50
Glaciers	Two orthogonal	6 mo	Yes	1 mo	TBD	10 ⁵	20
Water pollution	None	Weekly	Yes	2 d	None	10 ⁶	10

^bNot applicable.

them (ref. 5-5). In that study, the effect of the speckle is described quantitatively by a "gray-level resolution." The equivalent number of independent looks for a photograph is essentially infinite (because the illumination is not monochromatic), and the equivalent pixel dimensions for radar images with specific numbers of looks averaged can be obtained from that for a photograph by calculation. The best way to describe the required resolution is in terms of that required for a photographic image, and the radar designer can then modify the required pixel dimensions and number of looks to match the requirements of the user in the best way from a technological standpoint. Thus, the resolution listed in this column is that for an equivalent square photographic pixel.

For a few applications, specific measurements of the relative intensity of the backscattered radar signal are called for. An example is the measurement of soil moisture, for which a numerical value, rather than an interpretation, is required. In these cases, the required gray-level measurement precision has been indicated.

The requirement for geometric precision has been one of the most difficult to specify. Included are the requirements for transformation of the image to a format suitable for combining with other radar images and with images in the visible and IR regions of the spectrum. Also included is the precision needed in location so that the radar image may be used in connection with maps and other data to give specific geographic coordinates to a particular element observed.

The dynamic range required for an image is usually less than the total dynamic range required for a system. Most land and ocean surfaces exhibit relatively modest ranges of variation of the mean scattering coefficient at a particular incidence angle, but the center of this range may vary considerably from one class of area to another. For instance, the return signal from sea is usually much lower than that from land, but the user may need to expand this low-mean-value part of the possible signal range to detect fine gradations in the signal returned from the sea. Two columns in the table relate to this aspect: One column gives the dynamic range required (if properly centered) for a single data product, and the other column indicates the need for tailoring the dynamic range to cover different mean levels. The latter requirement can be met by expanding two parts of the range so that, for example, fine gradations in the water surface and fine gradations in the land surface can be seen on the same image. In many cases, however, a better way to meet this requirement is to provide multiple image products to the users of water data and the users of land data - or to the users of agricultural data and the users of urban data. The information for all the applications will be contained in the dynamic range of the radar itself; but because of the limited dynamic range of film, the radar range must be split to provide adequate images for the different applications.

The need for observation of the ground from multiple viewing aspects (azimuthal angles) is well established for geology. The reason is because shadowing and other effects of slopes in the mountains cause mountainous terrain to appear quite different from different viewing directions; much additional information is obtained by use of the views from the different directions. Because this effect is well known for geology, it can be

inferred that multiple viewing angles will be required for most applications in mountainous regions and for some others, such as the viewing of buildings in cities.

For some applications, frequent repeated coverage of the same terrain is required; whereas for others, although infrequent viewing is required, it must be timed well to coincide with certain natural events such as floods or snowmelts. For the applications requiring regular repetition, the column "Frequency of coverage" has been used to indicate the necessary repetition interval. For those applications wherein repetition is not important but timeliness is required, the need is indicated - sometimes with a period within which the imaging must be accomplished - in the column "Timeliness needs."

When frequent repetition or timely coverage is needed, the results must usually be provided to users quickly; for other applications, longer delays are possible. No matter how effective the spacecraft system and the image processing system are, the system for delivery of images to users could make the results of little value if it imposes too much time lag. Consequently, a column has been incorporated to specify the allowable lag time between the collection of the radar data and the delivery of the product to the user.

A few applications are critical as to time of day, primarily because of differences in the radar signal caused by diurnal effects. For instance, in monitoring snow, the results obtained in the middle of a cold night are quite different from those obtained at the high point of the solar heating during the day, when the snow may contain considerable water in unfrozen form. At lower microwave frequencies, vegetation exhibits diurnal variations in radar return. A column has been provided to indicate those applications for which such time-of-day effects are important.

Attempts have been made to identify the area of coverage required for the different applications. In some general application categories, this quantity is stated in terms of the total area within the 48 contiguous States that must be covered; and in other major categories, it has been stated in terms of the minimum size of coverage area required in a particular image to achieve the goals of the user. The area of the continental United States is taken as 10^7 km².

For some applications, continuous coverage of the area of interest is required; for others, success can be attained with the use of sampling techniques. This point has been considered and incorporated in the column "Extent of coverage."

In summary, one can say that a capability of processing multifrequency and multiple-polarization SAR data obtained at incidence angles ranging from 50 to 80°, obtaining imagery with a 25-m spatial resolution, a 1-dB gray-level resolution, a 20-dB dynamic range, and a 10-m geometric precision, will satisfy the requirements for most applications if the processed image data can be made available within a week of the SAR measurement.

Synthetic Aperture Radar (SAR) Image Quality

The SAR image quality can be determined by the measurement of a number of image quality parameters. To be most useful, an image quality parameter should be measurable from imagery alone. In most cases, a special scene must be imaged in order to make a measurement of an image quality parameter.

A number of image quality parameters are determined from measurements of the SAR system impulse amplitude response ($I(x)$). For optically processed imagery (which is, by implication, infinitely oversampled), the system impulse response can be obtained from a single image of a strong point scatterer in a low-reflectance background. A number of images, each having the point scatterer echo falling at different positions relative to the sampling grid, are necessary to evaluate the impulse response of a digitally processed SAR. The following image quality parameters are derivable from impulse response measurements.

1. Mainlobe width (MLW)
2. Clutter width (CW)
3. Flare ratio (f)
4. Integrated sidelobe ratio (ISR)
5. Peak range and azimuth sidelobe levels

Figure 5-1 illustrates the definition of some of these image quality parameters for the case wherein $I(x) = (\sin x)/x$.

The MLW is the width of the impulse power response, $S(x)$, at the 3-dB points relative to the peak response, where $S(x) = I(x) \cdot I(x)$. The MLW is related to the resolution of the SAR image but should not be mistaken for the resolvable distance, which is a better indicator of SAR resolution. The MLW should be determined in both the range and azimuth directions.

The CW is the width of a rectangle of unit height having the same area as that under the normalized impulse power response function. The CW is meaningful only if the impulse power response falls off faster than the reciprocal of the distance from the peak response. The CW cannot be estimated with perfect accuracy from imagery with a finite swath width, because the contributions to the CW from regions outside the imaged swath cannot be measured. The CW should also be measured in both the range and azimuth directions.

The flare ratio, f , is a parameter derived from the MLW and the CW.

$$f = (CW - MLW)/CW \quad (5-1)$$

The flare ratio has a maximum value of 1.0 and approaches zero as the impulse response outside the mainlobe approaches zero.

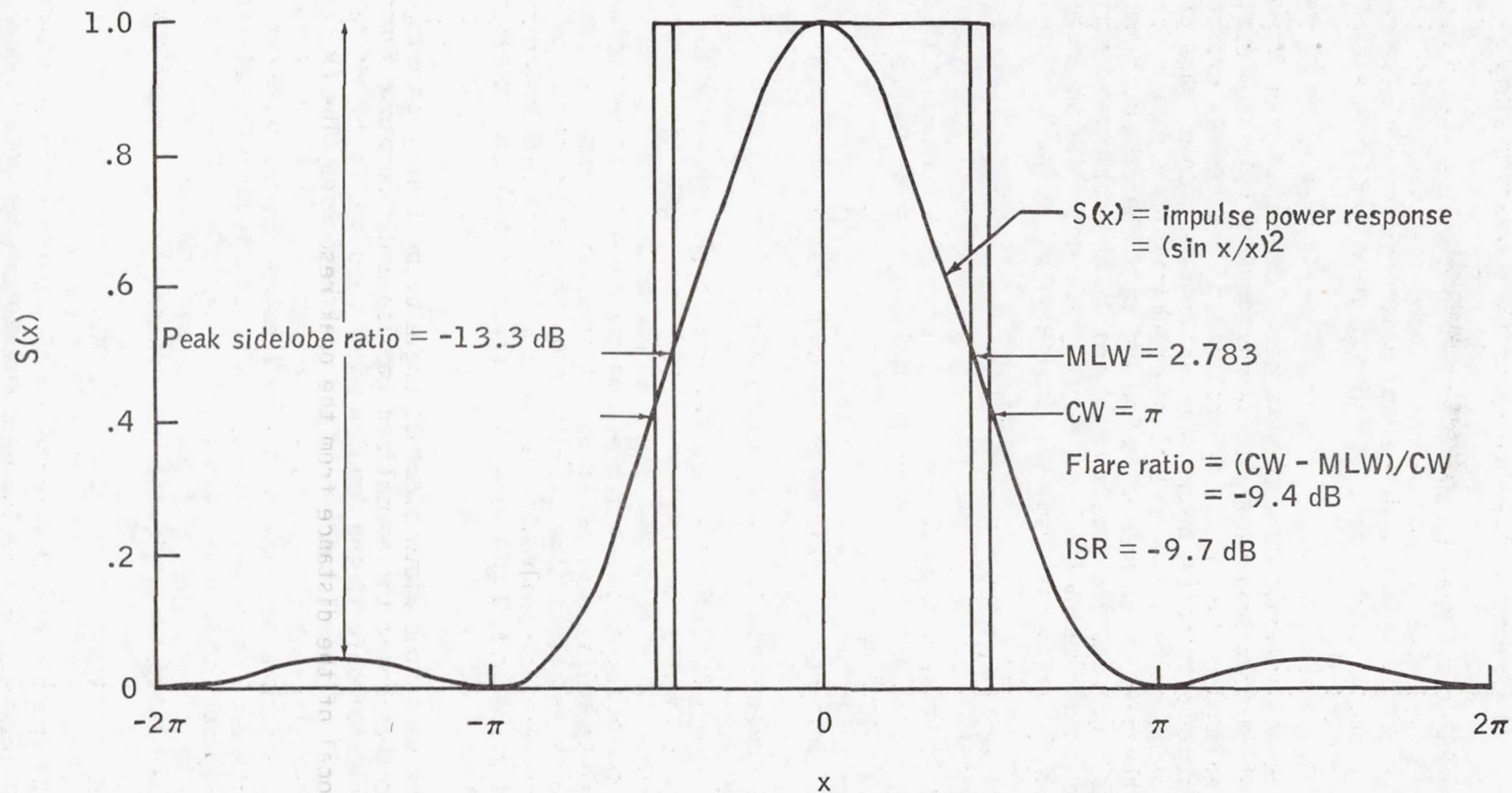


Figure 5-1.- An example of some image quality parameters obtained from measurements of the system impulse response.

The flare ratio is similar but not identical to the ISR, which is the ratio of the integrated impulse response in the sidelobe region to that in the mainlobe.

$$\text{ISR} = \frac{\int_{\text{sidelobes}} S(x) dx}{\int_{\text{mainlobe}} S(x) dx} \quad (5-2)$$

If the impulse response has no null separating the mainlobe from the first sidelobe or if the response monotonically decreases from the peak value, it is impossible to precisely define a boundary between the mainlobe and sidelobe regions. Thus, the flare ratio is preferred over the integrated sidelobe ratio as an image quality parameter.

The peak sidelobe ratio is the ratio of the largest peak in the sidelobe region of the impulse response to the maximum mainlobe response. Measurement of the peak sidelobe ratio is complicated by uncertainties in defining the mainlobe and sidelobe regions in the same way as for the measurement of the integrated sidelobe ratio.

The spatial resolution of a SAR system is best specified by the image quality parameter "X-dB resolvable distance." To measure this image quality parameter requires the imaging of pairs of equal point scatterers with different separations; and in the case of digitally processed imagery, a number of images are required to measure this parameter. The X-dB resolvable distance is defined as the separation between two equal-strength point scatterers that produces an X-dB minimum dip in the level of the image between the maxima associated with the source pair. For a finitely sampled image, the X-dB resolvable distance is a statistical quantity. This parameter should be measured in both range and azimuth.

Another important image quality parameter is background roughness, which is defined as the ratio of the standard deviation to the mean level of linear power noise-free image data from an extended uniform scene. The background roughness parameter is a measure of the amount of coherent speckle or fading in the image and is important in determining the precision with which a single-pixel echo power measurement represents the true mean image echo power.

The maximum contrast is the ratio of the maximum image level to the minimum nonzero level of linear power image data. The maximum contrast can be measured for any image and is limited by the sidelobes of the system impulse response and by the signal-to-noise ratio.

Dark-target contrast is defined as the ratio of the mean image level in an area of zero reflectivity to the mean level of a large surrounding uniform-reflectance background. The dark-target contrast is affected primarily by the sidelobe level of the system impulse response and by the signal-to-thermal-noise ratio.

Adjacent-sample contrast is an image quality parameter strictly applicable only to sampled imagery. Optically processed (infinitely oversampled) imagery has an adjacent-sample contrast of 1. Adjacent-sample contrast is defined as the ratio of the maximum image response to a point scatter to the average of the response in the adjacent pixels. This

parameter is strongly affected by the size of the minimum pixel spacing relative to the MLW.

Mean level is the average level of linear power image data. The mean level is an indicator of the average signal-plus-noise power in the image.

Noise level is the average level of the image in response to a system noise-only input. The system mean signal-to-noise ratio is the mean level minus the noise level, divided by the noise level.

Geometric fidelity is the rms positional error averaged over an image between the displayed locations of the echo from a point scatterer and the true locations of this scatterer. The center of the image is assumed to be located precisely, and the true positions of the scatterer must be known relative to this point.

Table 5-4 lists the image quality parameters measurable from imagery, the type of scene required for the measurement, the subjective image quality most directly measured by the parameter, and approximate values for the parameters that will produce acceptable quality imagery for most applications.

Preferred Data Formats

The user community requires two basic output products.

1. Image film or image prints ("pictures")
2. CCT's containing digital imagery and/or raw data

These products can be for one of two purposes.

1. Browsing over a large area of coverage to locate specific areas of interest
2. Intermediate/final analysis and information extraction from specifically selected and processed frames of data (e.g., a 100- by 100-km image at 25-m resolution)

The output products required for browsing will tend to be large in volume (that is, many frames), at a coarse resolution, and for a single polarization and frequency. On the other hand, final products will tend to be one frame or a few frames for the desired resolution and for specific polarizations, frequencies, and looks.

The most acceptable format for either the film or the CCT products is one compatible with those produced for Landsat data today. It is clear that user utilization of SAR data will be greatly helped by making the data presentation and products like those that the users are familiar with and equipped to handle.

TABLE 5-4.- SUMMARY OF IMAGE QUALITY PARAMETER REQUIREMENTS

Image quality parameter	Required scene	Quality measured	Range of acceptable values
Mainlobe width	Single-point target	Resolution	Less than one-eighth of the size of the smallest object to be identified
Clutter width	Single-point target	None	Not applicable
Flare ratio	Single-point target	Contrast	<-10 dB
Integrated sidelobe ratio	Single-point target	Contrast	<-10 dB
Peak sidelobe ratio	Single-point target	Spurious responses	<-15 dB
X-dB resolvable distance	Pairs of equal reflectors at different spacings	Resolution	Less than one-sixth of the size of the smallest object to be identified
Background roughness	Extended area of uniform reflectance	Speckle	<-6 dB
Maximum contrast	Any scene	Dynamic range	>25 dB
Dark-target contrast	Extended uniform scene surrounding an area of zero reflectivity	Shadow contrast	<-10 dB
Adjacent sample contrast	Single-point target	Crispness	Approximately one gray shade
Mean level	Any scene	Brightness	As required
Noise level	System noise only	Snow	<-8 dB relative to mean level
Geometric fidelity	An array of surveyed point targets	Distortion	Approximately one-half of the pixel spacing

Aircraft Experiment Requirements

In the development of a multimission digital SAR processor, radar data need to be gathered in digital form to be used in the verification of the particular processor implementation. Currently, implementation ideas exist for digital processors to meet spacecraft SAR-data-processing requirements; but when these processors are developed, their design must be verified as producing imagery of the required quality.

Users of SAR data have used optically processed data almost exclusively to date, and answers to some obvious questions concerning digitally processed SAR imagery do not exist or are not well known. Some of these questions are as follows.

1. What resolutions, peak sidelobe levels, and signal-to-noise ratios are required for specific applications?
2. How much should the output image spatial oversampling be?
3. How many looks are required to meet the needs of individual users?
4. What are the instantaneous (specular) and distributed target (diffuse) dynamic range requirements for users?
5. For digital processing of data with significant range migration, what are the spatial and quantization requirements for range migration correction?
6. What are the sources of error limiting the achievable calibration accuracy for SAR imagery?
7. For purposes of display of multilook data, should the looks be added linearly, by the square of the amplitude (power), or how? What is the impact of multilook on interpretability?

As time goes on, theoretical answers to all these questions may be available, but they will need to be verified. In the meantime, radar data will be acquired optically by the ongoing aircraft programs. A digital recording system should be installed in at least one of these programs and a library of raw data obtained so that digital data will be available when the digital processor is available. This accomplishment could significantly reduce the time lapse preceding NASA acquisition of an operational digital processor for SAR data.

Image Registration Accuracy

The basic requirement with respect to image registration accuracy is that "it be as good as possible and at least as good as for current optical imagery." This description means registration to the nearest pixel, as will be provided by the master data processor system being developed for the GSFC. Further, it is imperative that registration of SAR data to Landsat/thematic mapper data be provided.

ALGORITHMS AND ARCHITECTURE

The Algorithms and Architecture Subpanel was supplied with the following questions/instructions to guide its work.

1. What are the steps or operations required to process SAR imagery? Define the SAR-data-processing problem, starting with sensor in-phase/quadrature (I/Q) video signals and ending with finished output imagery and data.

2. Estimate the type and quantity of arithmetic operations required to perform the basic SAR-data-processing functions.

3. What are the most efficient algorithms that can be used to perform the SAR-data-processing functions?

4. What is the best processor architecture for a large ground-based SAR-data-processing system?

5. What is the minimum I/Q video quantization precision that will provide imagery satisfying the user requirements?

6. What are the input data requirements needed to produce imagery of the required quality?

Basic Principles of Synthetic Aperture Radar (SAR) Data Processing

Coherent integration is the basic principle underlying SAR data processing. To produce a SAR image of a given point in space from a sequence of coherent (vector) radar echo measurements made along an arbitrary trajectory, it is first necessary to calculate how the phase of an echo from a fictitious point scatterer at the given point would change from measurement point to measurement point along the trajectory. The radar echo vectors measured at each point are then rotated by the appropriate phase angles so that the echoes from a point scatterer located at the given image point would all be in phase; that is, would all have the same phase angle. The phase-adjusted received echoes are then summed, with the result that the echoes from the given point add coherently whereas echoes from other points sufficiently removed from the given point add incoherently and are thus suppressed by a factor equal to the number of samples coherently processed. The basic operations in SAR data processing are complex multiplication (required to perform the phase rotation) and summation. Although the fundamental principle of SAR data processing is a relatively simple concept, coherent integration, the implementation of this concept to yield useful imagery in a practical and economic manner is a decidedly nontrivial matter involving a number of complicated considerations.

Typical Steps Required in Processing Synthetic Aperture Radar (SAR) Imagery

In figure 5-2, the steps typically required to digitally process raw SAR sensor data into imagery are diagramed. These steps may be summarized as follows.

1. A/D conversion - Subsequent to the generation of a bandpass-limited analog video by the radar sensor, the information must be converted to digital form. This operation must be performed in synchronism with the sensor clock subsystem in order to retain system coherence and with a high timing accuracy in order to retain a low ISR.

2. PRF buffering - The radar system generates data at a less-than-unity duty cycle. To lower the data generation rate and utilize the interval between subsequent pulses more efficiently, a buffering operation should be performed.

3. Range compression - Spaceborne SAR systems will invariably use some method of transmitted pulse coding or dispersion to make use of available transmitter average power. Consequently, during the generation of the SAR image, a pulse compression operation must be performed. A number of techniques exist for performing this operation, two of which are as follows: (1) convolution or correlation compression and (2) fast Fourier transform (FFT), complex filter multiply, and inverse FFT. Variations in system gain can be compensated for at this time, and the appropriate array weighting for sidelobe control can be applied.

4. Azimuth prefiltering - This function is peculiar to the implementation in which separate processors are used for each look. For each of these processors, the azimuth time-bandwidth product required to attain the required resolution is much lower than the available azimuth time-bandwidth product. Consequently, to utilize the azimuth memory, it is advantageous to use bandpass filtering of the azimuth spectrum and thereby limit the data to the portion of that spectrum required by each look. Because the sampling rate after bandpass filtering generally exceeds the Nyquist rate, it is then also advantageous to resample the data. For the spacecraft applications for which this function is required, the Doppler spectrum centroid determination must be performed before the prefiltering function.

5. Data reformatting (or corner turning) - In processing steps 1 through 3, the SAR data are naturally required to be in a range-ordered format; in subsequent processing steps, the data are ordered according to the radar pulse repetition interval. Thus, it is necessary that the SAR data measured during an array be stored and read out orthogonally. This data reordering is sometimes called corner turning.

6. Doppler spectrum centroid determination - Because of the range migration compensations that must be performed because of the Earth's rotation, the spacecraft attitude control errors, and the orbital characteristics of the spacecraft, the center of the incoming Doppler spectra at different portions of the range swath must be adequately determined. This function must be performed before the range migration characteristics are

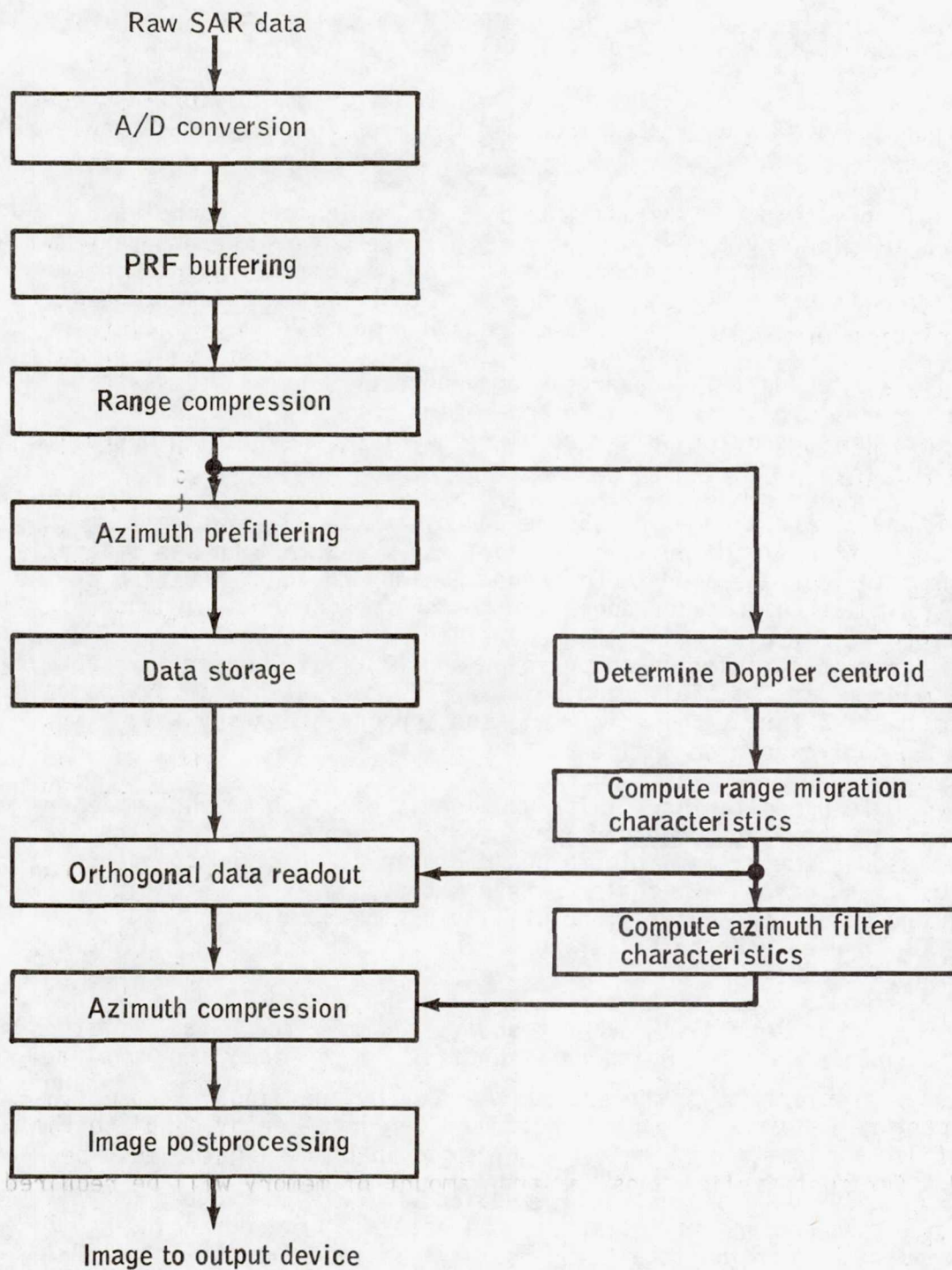


Figure 5-2.- Steps required in SAR data processing.

computed and, in the case of the separate-look processor, before the azimuth prefiltering and resampling.

7. Range migration compensation computation - The path that the echo from one point will take to pass through memory must be computed. The range migration characteristics are derived from the azimuth spectra centroid and target range.

8. Azimuth matched-filter computation - The azimuth matched-filter or reference function characteristics must be computed for different portions of the range swath. It is usually advantageous to store these characteristics in memory. For fully focused SAR, this matched-filter computation is range dependent and thus each range interval has a different matched filter.

9. Azimuth line readout and data point interpolation - Subsequent to the data-reformatting operation, the radar data must be read out according to the computed paths that a point target will take through memory. This data readout and transfer is routed to the azimuth compression device. This function will require either an interpolation between points - as the path that a point target takes through memory does not always pass through the discrete points - or a resampling of the data in range to account for this slippage.

10. Azimuth compression - Subsequent to the azimuth data readout, a one-dimensional compression must be performed. This operation, like the range compression operation, may be a correlation process in the spatial domain or a conversion to the transform domain, a complex multiplication against the matched filter and an inverse transform.

11. Image detection - Up to this point, all operations were of a complex form; i.e., two separate channels were employed - one in-phase (I) channel and one quadrature (Q) channel. The magnitude of the vector processor output at each data point is computed by squaring the two corresponding data points in the I and Q channels, adding them, and obtaining the square root. At this point, a single-look image is obtained.

12. Separate-image delay - For the separate-look processor, each look is separated spatially from the subsequent look by the length of the synthetic aperture required by each look. Thus, an image delay equal to the number of looks minus one, times the synthetic aperture length, must be provided. For most applications, a large amount of memory will be required for this delay. At the end of each of these delays, an image line addition must be made.

13. Image formatting and readout - The output image display will take a form that is proportional to either the amplitude of the signal, the power of the signal, the logarithm of the signal power, or some alternate encoding scheme. Thus, a reformatting operation must be performed. In general, many of these functions may be performed in different orders because the operations are primarily linear. The driving functions to the architecture may be technological in nature, but - in any case - they must be performed.

These steps must be performed regardless of the implementation method employed. However, steps 4 and 12 (azimuth prefiltering/resampling and separate-image delay) are peculiar to the technique in which separate processors are employed for each of the multiple looks generated.

The steps required to process SAR data depend somewhat on how the multiple-look postprocessing is implemented. The two basic methods of implementing a multiple-look processor are as follows: (1) Process the radar data to the ultimate resolution and subsequently degrade the final image by a noncoherent process or (2) process the data to the required resolution for each look separately and then noncoherently add the separate images together.

Each method offers some advantage over the other, and which method is optimum is highly technology dependent. However, the following statements can be made regarding each of these two classes of processors.

Fully focused processor.- The architecture of the fully focused processor is simpler than that of the partially focused separate-look processor in that some functions are not required. However, the number of azimuth cells in each range bin is much larger than that required by the separate-look processor. The result is that a larger azimuth memory is required, as well as a larger azimuth compression device. The effect of multiple looks is obtained by degrading the output product by averaging adjoining cells. Furthermore, the problems of range migration and depth of focus both increase as the square of the length of the processed aperture; so the relative architectural simplicity of the fully focused processor is more apparent than real.

Separate-look processor.- The operation of the separate-look processor is basically to process the radar data separately for each look and then subsequently add the images together. This implementation requires that the processor incorporate an azimuth prefilter and resampler or a separate local oscillator (LO) for each look. The number of picture elements (pixels) output by each look processed is much lower than that of the fully focused processor. This factor is, in its optimum sense, equal to the square of the number of multiple looks (N) required. However, N such processors must be used. After each look is processed, the separate images must be added together. Because each look is processed with a spatial separation from each other look, a reasonably large but slow buffer must be employed to provide this spatial image delay. This buffer is not required by the fully focused processor, and neither is the azimuth prefilter and resampler. Another disadvantage of the separate-look processor is that the exact characteristics for each look processed will be dependent on the system antenna attitude with respect to the Doppler coordinates, and the range migration compensation must take this effect into account. This problem is not severe for frequencies greater than 3 to 4 GHz because of the shorter required aperture; but the range migration problem is still present in the addition of the multiple looks, although it is simpler to accomplish at this point in the processing.

Arithmetic Operations in Synthetic Aperture Radar (SAR) Data Processing

Extensive processing of the radar return signals is required to produce a SAR image. The SAR data processing may be performed by using either digital or analog methods. The former method will be considered in detail here because the technology exists in this area to provide real-time or near-real-time processing.

For an all-digital approach to the SAR-data-processing problem, the radar return signals are sampled after a conversion to video frequencies. These samples must be processed as they are received or stored for future processing. In either case, the processing load is comparable and the types of arithmetic operations are similar. These operations are identified subsequently, and the quantity of each required to perform conventional SAR algorithms is estimated.

In general, computation involves the basic arithmetic operations - addition, subtraction, multiplication, and division. These operations (or their equivalent) are required in SAR data processing, but addition, subtraction, and multiplication are used much more frequently in the algorithms than division. This fact is fortuitous because digital processors inherently can perform addition, subtraction, and multiplication more rapidly than division, with less hardware.

In the SAR algorithms described in the previous section, the summation of amplitude-weighted and possibly phase-rotated received signal samples is required. For the general case of complex (in-phase and quadrature) samples, amplitude weighting requires multiplication of a real number by a complex number (or equivalently, two real multiplications), phase rotation requires multiplication of two complex numbers (or equivalently, four real multiplications and two real additions), and summation requires an addition of two complex numbers (or two real additions). Other frequent computations, such as an FFT, represent combinations of the functions previously described. The basic element of the FFT, the butterfly, consists of one complex multiplication followed by two complex additions (ref. 5-6).

The processor should be designed with adequate word length so that the great majority of computations can be performed with single-precision arithmetic. Double-precision arithmetic has a time penalty associated with it. However, there is generally some double-precision arithmetic required in a processor that is designed for cost economy. This type of computation is usually not performed on data samples. Rather, it is performed for control functions, where the error in the least significant bit of some quantity can propagate - because of iterative operations - to more significant bits and thus possibly result in unacceptable image quality. An example is the interpolation and resampling of data in which the integral portion of a computed control word represents the location of the resampled data and the fractional part of that word represents the location of an original sample relative to the desired location of the resampled data.

Division by individual radar samples is never required. There are occasions when division by a date-derived number is required, such as for

automatic gain control (AGC) operations; but when this instance occurs, the same divisor is used repetitively. In this case, the proper computational procedure would be to invert the divisor by dividing unity by it and use this result as a multiplier in subsequent calculations.

A time-saving technique for generating functions required frequently is to store in a table samples of the function corresponding to values of the independent variable. Obtaining a value from a table is much more rapid than computation of the value. Examples of where this arrangement is useful are applications in which amplitude weighting is required or the logarithms of samples are required.

Because of the large amount of data that must be stored to produce large images and the usual requirement that they be accessible in sequence in either of two orthogonal dimensions, data or memory management places demands on the processor regardless of the storage medium. The amount of computation required for this function is greatly dependent on the memory architecture. However, if the memory is dedicated to a particular task, supervision of it is not a large or difficult task.

Data-dependent branching is not required in a SAR processor, although branching may occur on the basis of the locations of the data samples. There are ways to handle almost any SAR-data-processing function, however, without branching. This fact has important architecture implications for both the arithmetic unit of the processor and the memory.

Various techniques have been developed that reduce the number of multiplications required for processing, primarily by trading multiplications for additions because multiplication is inherently more complex than addition. In any arithmetic unit, more time and/or hardware is required to perform multiplication than addition. One technique of achieving the trade is to convert all data samples into polar coordinates and take the logarithm of the magnitude and likewise of the amplitude-weighting coefficients. Then, for phase rotation, one real addition (on the angle) is required rather than a complex multiplication. For amplitude weighting, one real addition (on the magnitude of the datum) is required. Accumulation summation could be performed by means of a table lookup or by converting back to linear Cartesian coordinates and performing a complex addition.

A second efficient processing scheme that has been used is to substitute fast Walsh-Hadamard transforms for FFT's. Both the in-phase and quadrature parts of these transforms have unit amplitude; so multiplication is avoided in filter formation by this technique. The resulting filters have poor sidelobes, however, and extensive processing on the filter outputs is required to improve the shape of their passband. A performance equivalent to that obtained with FFT's is possible, but - in that case - subsequent filter-formation processing is expensive. The applicability of Walsh-Hadamard transforms is therefore confined to uses for which performance level requirements are not too stringent.

Quantity of Arithmetic Operations Required

An estimate of the number of each basic type of arithmetic operations required can be made for the most frequently used processing algorithms. Among the common ones, presum filtering, interpolation, the FFT, and convolution are estimated here.

In some SAR applications, only a portion of the real antenna beam is processed. (This is common in airborne strip map applications in which the azimuth resolution, wavelength, and antenna beamwidth are such that the rotation of the line of sight required for SAR processing is much less than the antenna beamwidth.) For space applications, however, the entire beam is generally processed. Presumming still has application here because usually only a portion of the beam can be processed with the same corrections for platform motion, Doppler curvature, and range walk. Presum filtering is then often performed to reduce the Doppler bandwidth of the received data so that it corresponds to the extent in azimuth of the desired image patch. The amount of data that must be stored in memory is reduced by presumming. For presum filtering, the requirement is merely amplitude weighting for shaping and summation if the filter is to be centered at zero frequency. At any other center frequency, a phase rotation would be required as well. On the assumption that the amplitude weighting would be imposed on the phasors before the data samples are presumed and that the data samples from a pulse are spread uniformly in time over the interpulse period through buffering, the computation rate required for presumming in real time is $\kappa f_r N_r$ complex multiplications and additions per second for each presum Doppler band. In this case, f_r is the PRF, N_r is the number of range samples, and $1/\kappa$ is the portion of azimuth samples in the presum input array that are not common to those in the subsequent presum input array. For space applications, a typical value for f_r is 1500 Hz and N_r might be 4096. The array overlap factor, κ , is typically between 2 and 4. For $\kappa = 2$, the computation rate for presumming in this example is 12.3×10^6 multiplications and additions per second. If the data are recorded before processing, the computation rate could be reduced considerably provided the data collection duty factor is small.

Interpolation and resampling can generally be combined with presumming. In cases wherein the PRF is not sufficiently greater than the desired presum filter bandwidth, interpolation may require a larger κ factor (more input array overlap) to obtain adequate image quality. For one-dimensional cubic convolution interpolation, which is a commonly used compromise to the optimum $(\sin x)/x$ interpolation scheme, κ cannot exceed 4.

An FFT on N points requires $(N/2)\log_2 N$ butterflies or, equivalently, that many multiplications and twice that many additions. For a two-dimensional $M \times N$ array of data on which an FFT is to be performed in two orthogonal dimensions, $MN(\log_2 N + \log_2 M)$ butterflies are required (on the assumption that M and N are powers of 2). (Some slight additional penalty results if M or N is not a power of 2.) An array of $N_r = 4096$ (samples in range), for example, and $M = 512$ (samples in azimuth) requires 44×10^6 butterflies.

Convolution can be performed in the time domain or in the frequency domain. If it is performed in the time domain by brute force, the number of multiplications and additions per pulse is $N_r P$, where P is the pulse compression ratio. For typical numbers of $N_r = 4096$ and $P = 512$, 2.1×10^6 multiplications and additions are required per pulse. A more efficient method of performing pulse compression exists when the compression ratio is large. It requires transforming the data samples, multiplying the result - term by term - by the transform of the pulse compression waveform, and taking the inverse transform of the product sequence. The number of multiplications required to perform pulse compression by this method is $N_m = (N_r + P) \log_2(N_r + P) + N_r + P$, on the assumption that $N_r + P$ is a power of 2. The number of additions is $N_a = 2(N_r + P) \log_2(N_r + P)$. For the parameter values previously supposed, $N_m = 65 \times 10^3$ (number of multiplications) and $N_a = 120 \times 10^3$ (number of additions), where $\log_2(N_r + P)$ is rounded off to an integral value. A 32:1 savings on multiplications and a 17:1 savings on additions are achieved relative to time-domain compression.

Synthetic Aperture Radar (SAR) Data Processing Techniques

In the previous subsections, the essential processing procedures required to convert SAR signal histories into imagery were established. The required operations are sufficiently general such that many implementation schemes exist. In this subsection, several techniques commonly proposed for SAR image formation processing are documented.

The discussion here will focus on purely digital processing technology. It is evident, however, that many applications could successfully rely upon the more conventional optical processing media (refs. 5-7 to 5-10). In addition, several hybrid approaches appear feasible that make use of analog-signal-processing elements as major links in the SAR-data-processing chain. The latter includes configurations that employ CCD's for both memory and signal processing (ref. 5-11), as well as systems utilizing surface acoustic wave (SAW) devices for signal compression (ref. 5-12).

Rather than seriously diluting this rather brief presentation of SAR data processing with a discussion of alternate processing media, a purely digital approach to the problem will be concentrated on in this report. However, where possible, references will be made to those processing steps that are amenable to economic application of alternate processing media.

Decomposition into Range and Azimuth Processing

As indicated earlier, conventional SAR systems obtain range resolution by transmitting dispersed pulses and applying pulse compression techniques to the returned signals. Azimuth resolution is obtained by recording the Doppler frequency shifts associated with returns from point scatterers as they migrate through the antenna beam. Knowledge of the Doppler-frequency-versus-time relationship for a point scatterer at a given range enables one to precisely locate the scatterer in azimuth in a manner analogous to application of the pulse compression in the range dimension. In this manner, the SAR processor functions essentially as a

two-dimensional filter matched to the signal generated by a point scatterer during the period that the scatterer is illuminated by the antenna beam.

To a first order, the two-dimensional processing function can be separated into two orthogonal, one-dimensional, pulse-compression steps (ref. 5-9). This apparent simplicity must be tempered by the fact that the azimuth compression filter varies as a function of the range distance associated with the data being compressed in the azimuth dimension. Thus, on the basis of the resolution requirement for a given system, a specific azimuth filter may be adequate for only a small portion of the desired range coverage. For shorter SAR wavelengths and gross resolutions, this problem is minimal. The usual digital solution to this problem is to implement a sufficient number of azimuth filters to obtain the required resolution over the desired range interval.

An additional complication is associated with the separable and orthogonal notion of range and azimuth processing. Many SAR imaging geometries imply that a point target does not remain within a single range-resolution interval during the synthetic aperture period. In reality, the scatterer can migrate through many range cells, either because a constant range from the antenna is represented by a sphere (range curvature) or because a need exists to image with the radar antenna squinted either fore or aft of broadside. These two effects are illustrated in figure 5-3. For a spaceborne SAR with long synthetic aperture intervals, the Earth's rotation can also cause a range-walk effect.

Uncompensated, these effects cause both range and azimuth target smearing to occur. If the resolution requirements are sufficiently stringent, the range migration must be compensated for. By using a stationary, flat Earth assumption, it can be shown (ref. 5-3) that range curvature will exceed one-half of the range resolution for slant range R such that

$$R > \frac{16\rho_a^2\rho_r}{\lambda^2 K_a^2} \quad (5-3)$$

where

ρ_a = required azimuth resolution

ρ_r = required range resolution

λ = radar wavelength

K_a = array factor

Similarly, range walk must be accounted for in operating ranges such that

$$R > \frac{\rho_r \rho_a}{K_a \lambda \tan \alpha} \quad (5-4)$$

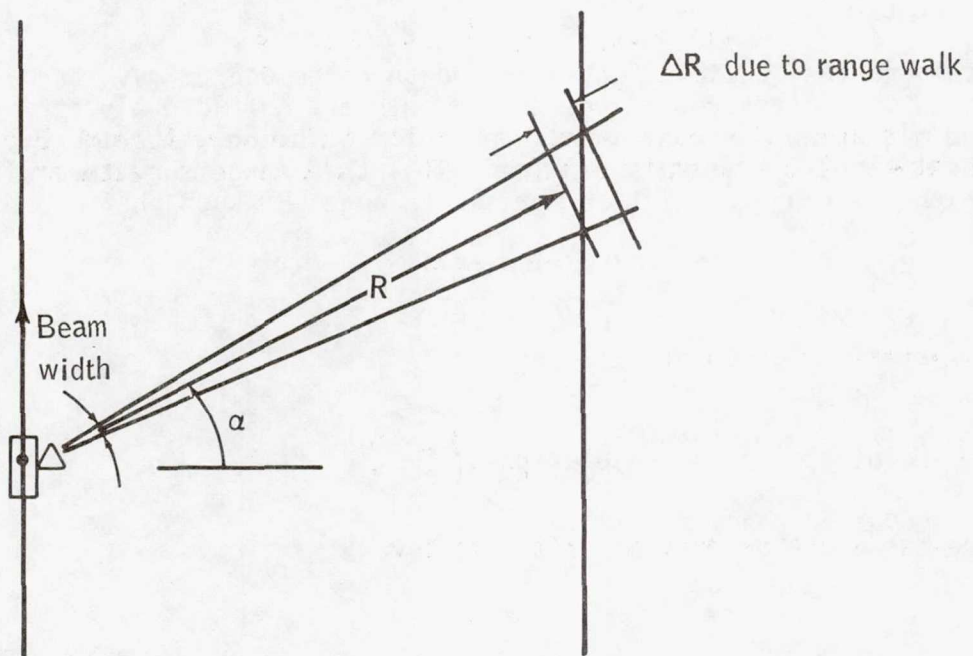
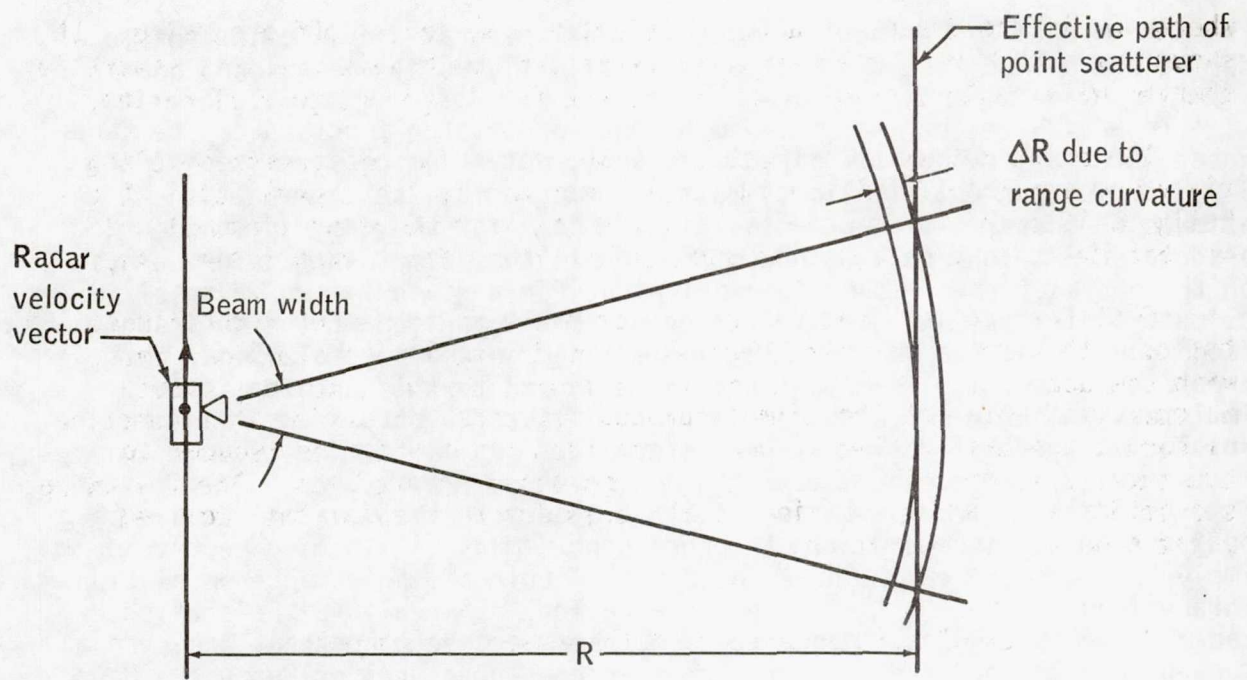


Figure 5-3.- Range migration of point scatterer due to SAR imaging geometry.

where α is the amount of angular (slant range) squint off broadside. It should be noted that both range curvature and range walk are less severe for shorter wavelength systems and more severe for longer range applications.

The range migration effects are compensated for by processing along tilted or curved azimuth apertures or lines within the signal data. Digitally, this compensation can be performed by interpolating (resampling) the SAR data in the range dimension before the azimuth compression step.

Once the range-migration correction procedure has been accomplished, the azimuth compression step becomes a one-dimensional operation. Thus, with the acknowledgement that the range migration must, in many cases, be corrected and that the azimuth processing function varies as a function of range, the basic SAR-data-processing requirements can be reduced to two successive one-dimensional pulse compression procedures. The following subsection will address various techniques for performing the required pulse-compression operation.

One-Dimensional Pulse Compression Techniques

If it is assumed that a linear frequency modulation (FM) scheme is used by the radar, the pulse to be compressed in range can be expressed as

$$s(t) = \exp(-\pi i \frac{B}{\tau} t^2), \quad -\frac{\tau}{2} \leq t \leq \frac{\tau}{2} \quad (5-5)$$

where B is the pulse bandwidth, τ is the pulse length, and B/τ equals the FM rate of the transmitted pulse. The instantaneous phase of $s(t)$ is

$$\phi(t) = -\frac{B}{\pi\tau} t^2 \quad (5-6)$$

The instantaneous frequency is

$$\nu(t) = \frac{1}{2\pi} \frac{d\phi}{dt} = -\frac{B}{\tau} t \quad (5-7)$$

The time-bandwidth product of $s(t)$ is simply

$$K = \tau B \quad (5-8)$$

K also represents the compression ratio attainable when $s(t)$ is passed through the matched filter.

$$\begin{aligned} h(t) &= s(-t) \\ &= \exp\left(\pi i \frac{B}{\tau} t^2\right), \quad -\frac{\tau}{2} < t < \frac{\tau}{2} \end{aligned} \quad (5-9)$$

The signal $s(t)$ represents the complex modulation of the transmitted signal. However, if $t = x$ (along track position) and $B/\tau = 2/R\lambda$, then equation (5-5) represents the azimuth signal from a broadside point target at slant range R .

Convolution Pulse Compression

Pulse compression consists of forming the convolution

$$\begin{aligned} a(t) &= h(t) \cdot s(t) \\ &= \int_{-\tau/2}^{\tau/2} h(t-u) \cdot s(u) du \end{aligned} \quad (5-10)$$

where $s(t)$ is the range or azimuth signal, τ is the signal duration, and a is the filter output.

In a digital processing system, $h(t)$ is replaced by its sampled equivalent.

$$h_k = (k \Delta t) = \exp(\pi i k^2 / K) \quad (5-11)$$

where

$$k = -\frac{K}{2}, \dots, 0, 1, \dots, \frac{K}{2} - 1$$

$\Delta t = 1/B$ is the maximum sampling interval, and $K = \tau/\Delta t$ is the minimum number of samples.

Then if s_n is the sampled signal, the filter output is given by the discrete convolution

$$\begin{aligned} a_n &= h_n \cdot s_n \\ &= \sum_{k=-K/2}^{k=(K/2)-1} h_k s_{n-k} \end{aligned} \quad (5-12)$$

Direct implementation of the convolution (as shown in fig. 5-4) requires K memory cells and K operations for each output point, where K is equal to both the filter length and the compression ratio and an operation is defined as a complex multiplication plus a complex addition.

Often, these "brute force" requirements for arithmetic operations and memory cells are unacceptably high. Various alternative schemes exist whereby one may, under certain conditions, gain in both computational and memory efficiency.

Fast Convolution by Using the Fast Fourier Transform (FFT) Algorithm

One method of improving computational efficiency in some cases is to use the fast Fourier transform (FFT). To illustrate its application, consider the convolution of the sequences h_n ($n = 0, 1, \dots, N_1 - 1$) and x_n ($n = 0, 1, \dots, N_2 - 1$). Let $N_2 > N_1$ and let

$$a_n = h_n \cdot s_n \quad (5-13)$$

be filtered sequence. Then, the sequence a_n has length

$$N_3 = N_1 + N_2 - 1 \quad (5-14)$$

However, the interval over which the output a_n is weighted by the entire filter sequence h_n is equal to

$$N_F = N_2 - N_1 + 1 \quad (5-15)$$

This point is illustrated in figure 5-5. To perform the convolution of equation (5-10) by using the FFT, append enough zeros to the sequences x_n and h_n to increase their lengths to N_3 . Then take the discrete Fourier transform (DFT) of the extended sequences, using the FFT algorithm; i.e., let

$$S_m = F(s_n) \quad (5-16)$$

$$H_m = F(h_n) \quad (5-17)$$

where F is the FFT operator. Then, by the convolution theorem, the DFT of a_n is given by

$$A_m = S_m H_m \quad (5-18)$$

Then a_n is given by the inverse DFT of A_m ,

$$a_n = F^{-1}(A_m) \quad (5-19)$$

which forms the desired compressed-pulse output.

The efficiency of this approach results from the inherent efficiency of the FFT for large sequences (large N_3). However, the penalty in terms of additional memory requirements for zero padding and reference spectrum

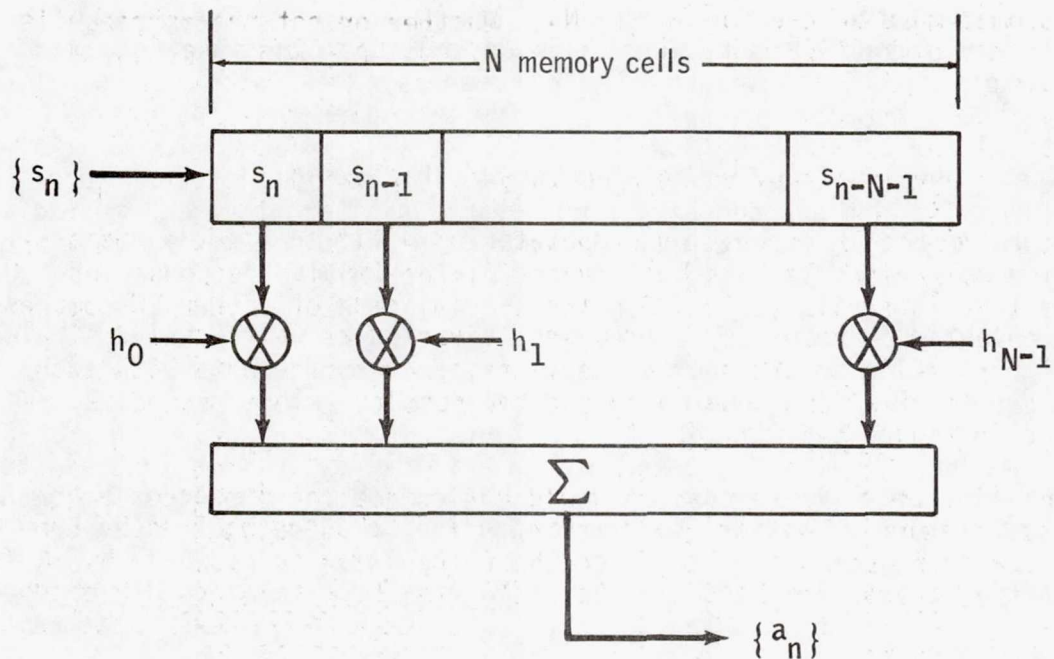


Figure 5-4.- Direct convolution pulse compression.

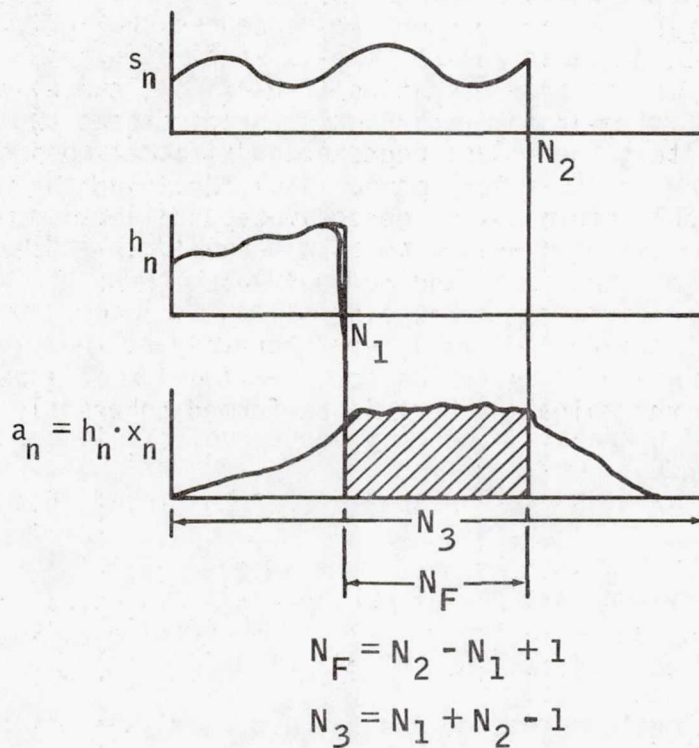


Figure 5-5.- Convolution of finite-length sequences.

storage becomes more severe for large N_3 . Whether or not the approach is warranted for a given system configuration depends upon the radar parameters involved.

Convolution by Using Frequency Multiplexing

A second method of increasing computational efficiency while decreasing memory requirements is to subdivide the filter impulse response into N contiguous time intervals (which, for the special case of linear FM compression, conveniently corresponds to frequency division as well), build simpler filters corresponding to the shorter sections, process the data with each filter, and then delay and coherently add the results. This method is illustrated in figure 5-6 for $N = 4$.

Ordinarily, this implementation would not reduce the number of operations or save memory. However, for a chirp pulse, the savings can be substantial because reducing the length of the filter impulse response by N simultaneously reduces the bandwidth to B/N and the time-bandwidth product to K/N^2 .

The passbands of the individual filters are ideally nonoverlapping. If the filters are used for azimuth focusing, the first filter, $h_1(t)$, processes the leading edge of the antenna beam or highest Doppler frequencies, and the last filter processes the trailing edge or lowest Doppler frequencies. Hence, the individual filter inputs can be preceded by bandpass filters and resampled at the lower rate, B/N , to reduce the individual filter computation rates. This procedure also reduces the individual filter memory sizes and required operations to K/N^2 . At first glance, in considering that there are N channels operating in parallel, there is an apparent savings in both number of operations and memory proportional to K/N . However, the bandpass filters themselves represent additional computational operations, and the requirements for appropriately delaying the multichannel data before the coherent recombination necessitate additional memory. In addition, it is impossible in practice to obtain the idealized bandpass filters; this constraint implies a required overlap between the channels and a resulting erosion of the apparent algorithm efficiency. Once again, the applicability of the technique will depend heavily on the radar system parameters. This technique is analogous to the azimuth multilook technique except that the recombination here is performed coherently.

Pulse Compression by Frequency Analysis of Dechirped Pulse

Another method of pulse compression is to dechirp the input data by multiplying it by a chirp reference and then perform a spectral analysis on the residual data as shown in figure 5-7. For efficiency, the spectral analysis is performed with use of the FFT algorithm.

A more efficient method of doing the spectral analysis after dechirping is to use a two-stage FFT algorithm in a manner analogous to use of the two-stage correlation algorithm discussed previously. In the first stage, the input sequence is dechirped over an interval of length N , which is less than the total pulse length. This sequence is filtered by using

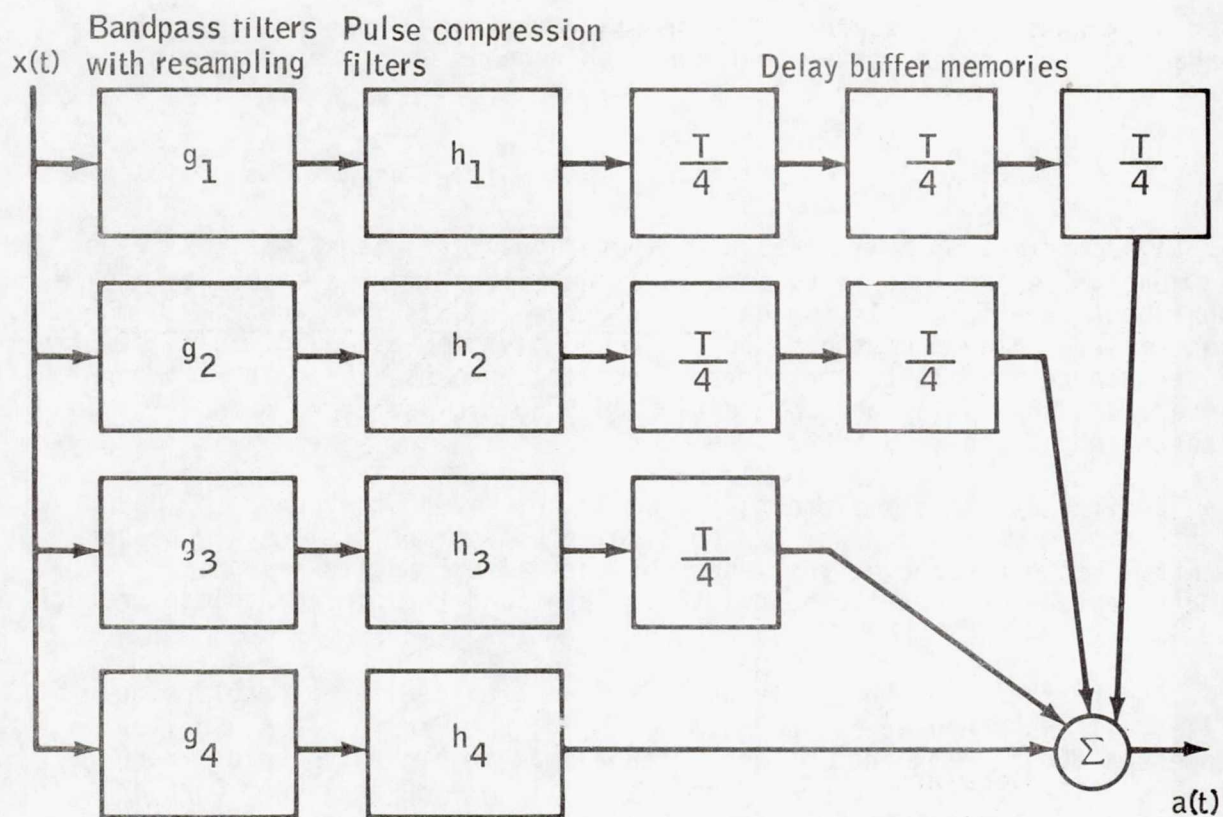


Figure 5-6.- Frequency-multiplexed pulse compression system.

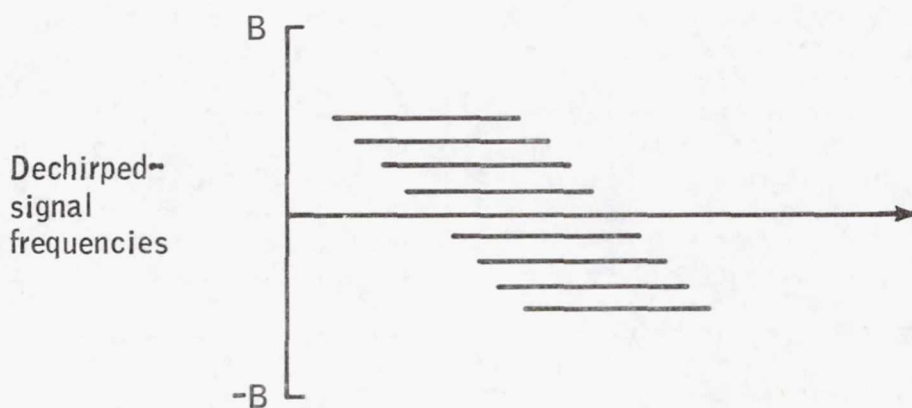
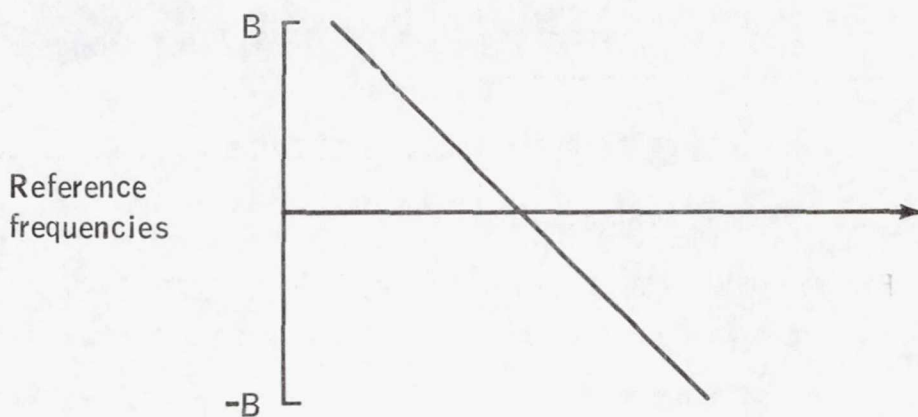
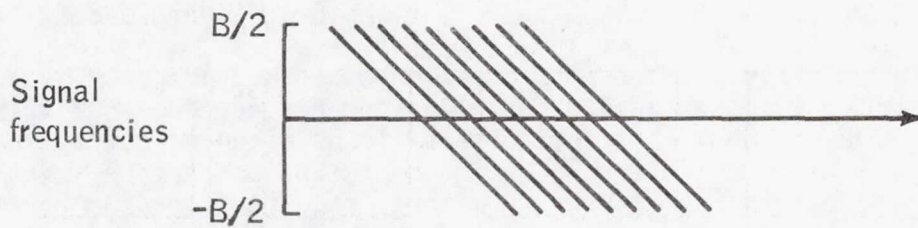
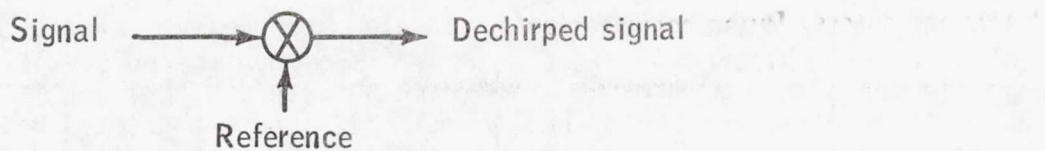


Figure 5-7.- Frequency-time diagrams of Fourier transform pulse compression processor.

the FFT algorithm, and the results are resampled and delayed for the second-stage FFT. If the chirp pulse has a negative FM slope, the pulse energy successively travels from the highest frequency filter to the lowest. By introducing more delay for the highest frequency filter, the total history of a single target can be a simultaneous input to the second-stage FFT filter. The target is then resolved by additional dechirping and filtering. A block diagram of the two-stage FFT is shown in figure 5-8.

After the first stage of processing, the data produced by a single FFT element are, essentially, partially compressed, low-resolution, complex-valued data. This fact often affords a convenient opportunity to provide motion compensation and range migration corrections with computation rates potentially reduced from those required for a brute-force approach. The relative efficiency of the approach obviously depends upon system parameters.

Each of the one-dimensional pulse compression algorithms previously described is applicable to either range or azimuth processing. The configuration of one-dimensional processing steps into a two-dimensional SAR-data-processing algorithm is the subject of the following subsection.

Two-Dimensional-Processor Organization

With the existence of suitable one-dimensional pulse compression technology, a SAR two-dimensional processor can be implemented in a number of configurations. The basic decision involves the selection of the order in which the "orthogonal" range and azimuth compressions are performed. Either the range or azimuth dimension may theoretically be processed first, although the impact of process sequence on processor memory requirements and on motion compensation techniques usually dictates the order of processing for a given application.

The processor configuration illustrated in figure 5-9 depicts the range compression being performed before the processing in the azimuth dimension. The first step in processing is usually a PRF buffering operation that provides for a real-time peak-data-rate reduction by spreading the data contained in a signal radar return over the entire interpulse period associated with the PRF. The second stage consists of an azimuth prefilter, which - for a single-look system - is essentially an azimuth low-pass filter and resampler that reduces the Doppler bandwidth and data rate to that required to obtain the desired resolution for the number of azimuth looks to be processed. For multilook operation, the azimuth prefilter could provide several independent channels of data for subsequent parallel processing. Figure 5-9 depicts a single-look system configuration.

The image formation processing of SAR data must, of course, compensate for the non-straight-line motion of the antenna phase center during the synthetic aperture interval (ref. 5-13). This compensation usually involves some adjustment of the range-sampling intervals (range gating) and adjustment of the signal phases as a function of instantaneous range to the various range intervals. If these operations are not performed as part of the receiver and digitizing operations themselves, they must be incorporated as part of the processing operations. Auxiliary motion and

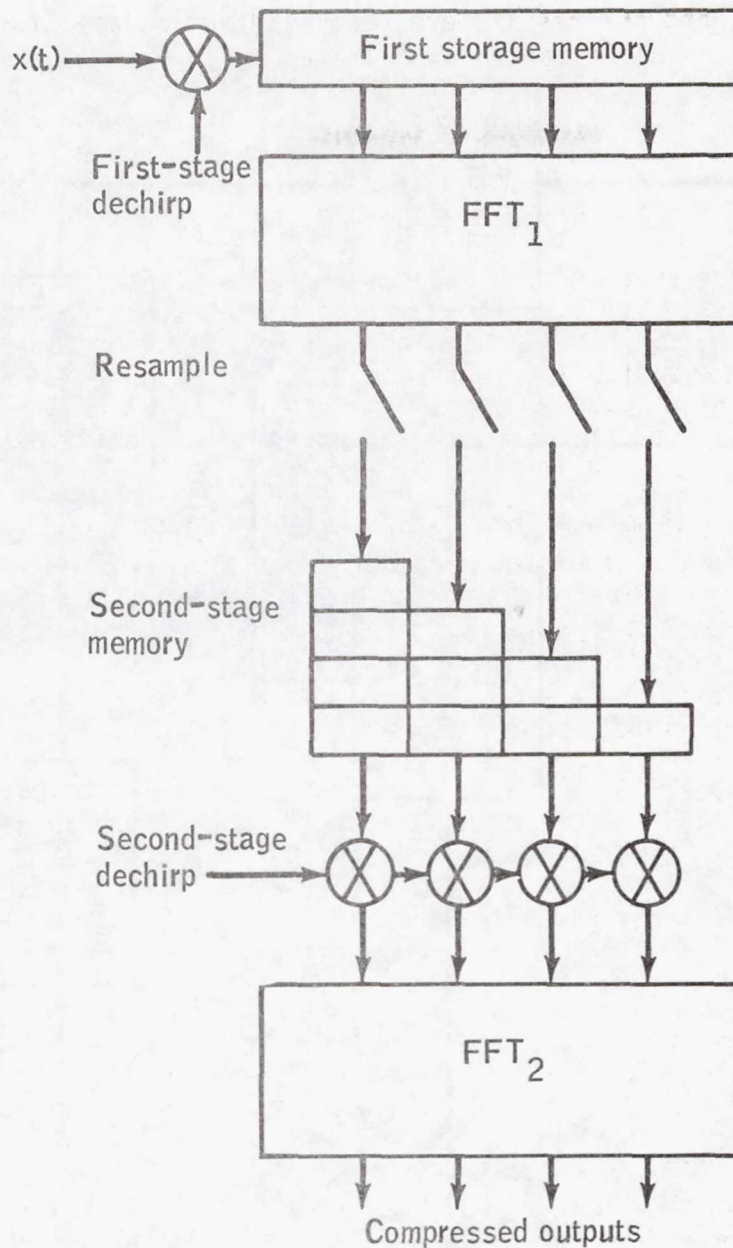


Figure 5-8.- Two-stage FFT pulse compression processor.

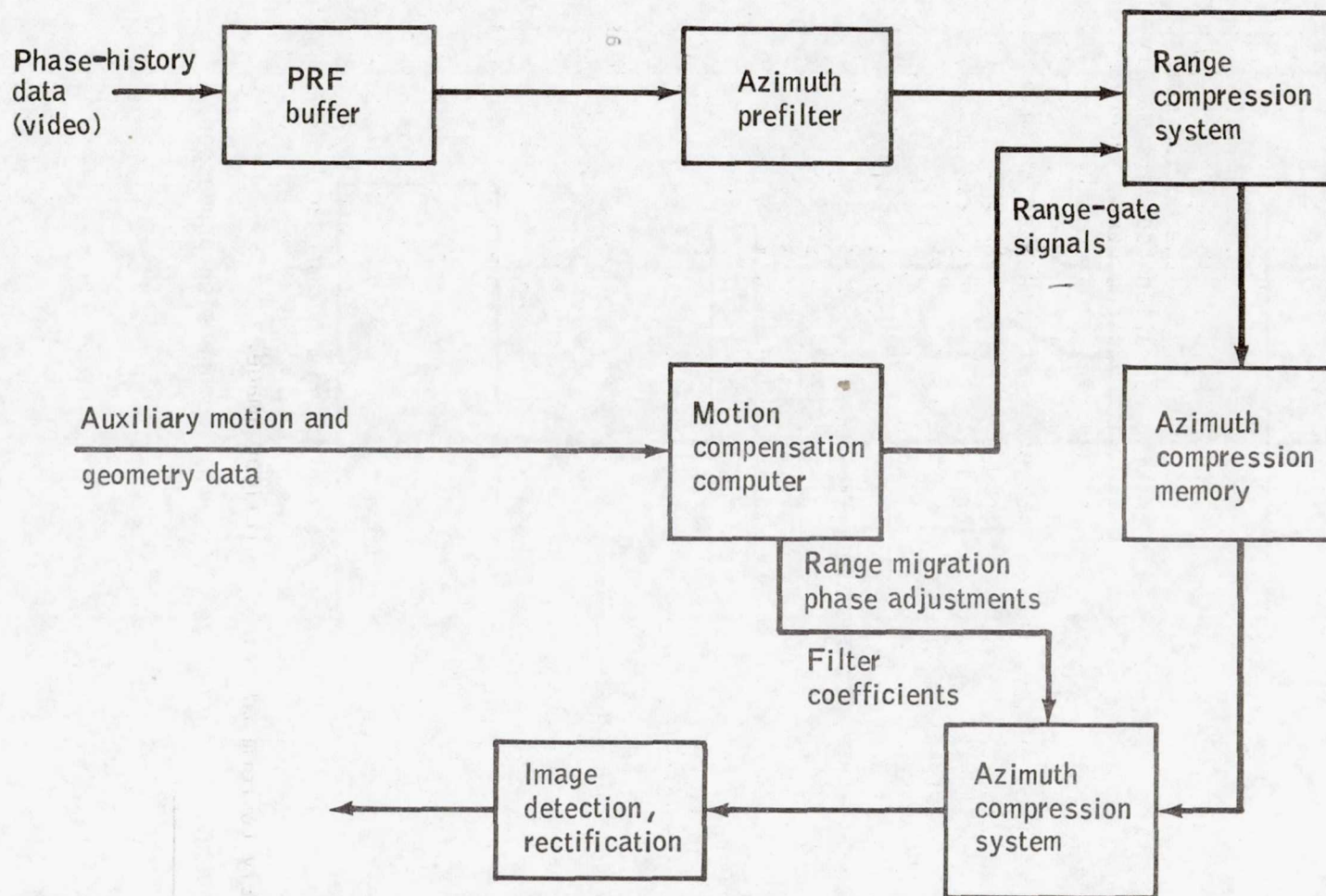


Figure 5-9.- Single-look SAR processor configuration.

imaging-geometry data must therefore be provided to permit computation of the required sampling and phase perturbations. A separate computing module is often incorporated for this purpose.

As illustrated in figure 5-9, a buffer memory must be provided before azimuth compression to permit accumulation of all the data corresponding to a synthetic aperture. Once accumulated, the azimuth data can be pulse-compressed by using filter coefficients generated by the motion compensation computer. (The coefficient-generating operation consists mainly of computing the Doppler FM rate associated with various range intervals traversing the scene, as perturbed by extraneous platform and Earth movement.)

As was stated earlier, the optimum order of range and azimuth processing is based on a trade-off between required memory size and processor complexity. A consequence of the pulse compression is that the instantaneous amplitude of point target returns is increased by the square root of the compression ratio. Thus, the dynamic range (i.e., word length) of the memory following the first stage of processing must be increased proportionally. The length of the memory associated with range compression is essentially equal to the number of range elements multiplied by the azimuth compression ratio.⁸ Thus, from a memory perspective, it is desirable to do azimuth compression first. However, because the azimuth compression (and often motion compensation and range migration correction) is performed as a function of range, it is sometimes desirable to perform range compression first. The final choice depends on the actual processing parameters associated with a given application.

Utilization of the more exotic pulse compression schemes (such as the two-stage FFT technique described in the previous subsection) affords more flexibility in processor operations sequencing. The multistage processing approach permits an interlacing of partial range and azimuth compression with use of the basic two-stage dechirp and spectral analysis approach. Such a scheme may be somewhat advantageous in terms of computation rates, memory requirements, and convenience of compensating for motion perturbations. In addition, some convenience with respect to multimode processing of multilook data may be possible. If single-look, full-resolution data are required, the final range and azimuth compressions can be performed as depicted. However, if multiple range and/or azimuth looks are desired, the partially compressed data could potentially be detected and combined noncoherently to form the final multilook image.

⁸If the range and azimuth resolution cell sizes are given in feet, the bulk memory size of the processor is

$$M = \eta N_0 R \lambda W (K_a / \rho)^3 N_b \text{ bits}$$

where η is the memory utilization factor ($0 < \eta \leq 1.0$), which is a function of the efficiency of the azimuth processing algorithm, N_0 is the number of noncoherent integrations, R is the range to midswath, λ is the wavelength, W is the swath width, K_a is the pulse-broadening factor, which is a function of aperture weighting, and N_b is the memory word size for the in-phase or quadrature component.

The actual choice of processor architecture will depend heavily on the radar system parameters and on the availability of new-technology hardware components. For example, if memory costs continue to decrease to the point of no longer dominating the processor costs, then less emphasis would be placed on memory reduction schemes and perhaps more on overall processor complexity reduction. In addition, for many applications, the range and/or azimuth compression subsystems might justifiably be replaced with analog or hybrid analog-digital pulse compression networks, with a resultant decrease in overall system weight and power requirements.

Additional Processing Considerations

Additional SAR system considerations can greatly impact the aforementioned processor implementations. In particular, the following subjects have yet to be examined in the context of this document: (1) alternate modulation schemes, (2) autofocus requirements, (3) image rectification, and (4) multimode considerations. This subsection will provide some brief commentary concerning these key design issues.

Alternate modulation schemes.- The choice of radar pulse modulation as a linear FM may not, in some circumstances, be the best available. Other pulse modulation schemes may possess features that make them attractive from either a generation, recording, or processing point of view. In particular, certain approximations to the linear FM approach have been shown to result in computational savings in terms of compression (and generation).

Alternate modulation schemes should be considered and studied for Earth resources applications. A key component in these investigations would be an assessment of the impact on processor-architecture resulting from an alternative approach. For example, the use of binary phase-coded modulation may be a good approach for certain processor configurations.

Autofocus requirements.- As previously discussed, the compression of SAR phase histories into imagery requires knowledge of the relative motion between the antenna phase center and the terrain strip being imaged. The constraints on the accuracy of these motion measurements are quite severe. Over a synthetic aperture interval, the short-term antenna movements (introducing so-called high-frequency phase errors) must be known and corrected to a fraction of a wavelength. The long-term motion (principally the platform velocity) must be known to within a fraction of a percent to enable adequate focusing of the data. Errors in the velocity estimates cause azimuth defocusing (blurring) of the image data. Current and projected airborne systems do not have adequate inertial navigation capabilities to obtain the necessary long-term velocity accuracies. For a spaceborne system, this limitation may be considerably eased because of the smoother flight environment.

If velocity errors are present in the system, then either manual or automatic focus corrections must be made to correct for the erroneous estimate of Doppler FM rate. Optically, such a correction is easily made by simply moving lenses. Digitally, the correction involves changing the filter coefficients. The most difficult aspect of the digital problem is

sensing the amount of focus correction required. Many techniques have been proposed, and some successfully demonstrated.

A requirement for an autofocus capability as part of a spaceborne SAR imaging system would have a nonnegligible impact on the processor architecture and algorithm selection. The requirement depends on the resolution required for a given application and on the quality of the auxiliary motion information accompanying the signal data. An autofocus capability would probably be required to produce focused imagery of ships at sea.

Image rectification.- It appears highly desirable to have the final image data geometrically registered to a common projection format - perhaps compatible with the Landsat-D proposed image format. Range layover conditions must be ignored in this context because they will result in unavoidable registration errors. The image rectification can be performed as a two-dimensional interpolation of the final digital image. This approach is best if many diverse image mappings are eventually required.

However, if a standard projection can be accepted, it is possible to engrain the image rectification feature into the processor itself. This task is achieved by appropriately adjusting linear phase corrections and resamplings within the processor. Because some of the required operations are already performed in the processor, some hardware savings might be possible by incorporating the rectification into the image formation process itself.

Multimode considerations.- A SAR image formation processor can readily be optimized (in terms of hardware complexity) for a given imaging geometry and radar wavelength. However, if a single processing facility is expected to provide image data for a variety of imaging geometries and over a number of wavelengths, the design task is obviously more difficult. These multimode considerations must be examined.

As an example of a key processor component that is impacted by both wavelength and geometry, consider the brute-force-processor bulk memory requirements. As was given in footnote 8 (p. 242), the bulk memory requirement is proportional to both range and wavelength. Thus, a general-purpose-SAR-processor's memory must be flexible both in terms of size and organization. The impact of memory organization flexibility on certain block-oriented memory technologies (such as CCD's or block-oriented random access memories) may significantly decrease the suitability of such technologies to the general-purpose-processor problem; however, the use of suitably sized memory blocks may make these technologies acceptable even for flexible processors.

If the problems encountered in producing a multimode processor become severe enough, it may become necessary to build several simpler processors to perform the various roles. The multimode question should therefore be thoroughly examined with respect to the projected system applications.

Possible processor configurations.- The nature of the synthetic aperture process lends itself well to the use of any one of a large variety of processing techniques to produce images from the original data. Some of these techniques are more suited to ground processing of the data,

whereas others may not be as suitable for the ground station but because of low power consumption and small size are especially suitable for onboard processing. Some methods are particularly advantageous for relatively modest resolution processing but are not significantly advantageous for fine-resolution processing, whereas others seem to be more general-purpose methods but may be cumbersome for the modest-resolution case.

In all cases of synthetic aperture imaging, the use of averaging of multiple independent samples is called for (multilook). Interpretability of images is better if the spatial resolution is sacrificed somewhat to the multilook capability, as indeed it must be for low-resolution imagery. Thus, all processors considered have a multilook capability.

Optical processing has been the traditional method used, but it will not be considered in this discussion because of the limitations associated with the use of silver halide film as the data storage medium. If some hybrid storage medium with electronic input and optical readout can be found to replace film, optical processing may become the method of choice.

Useful processors using all-digital, all-analog (continuous or sampled data), or hybrid digital-analog techniques can be developed. The latter type appears to offer the most promise for small onboard systems, but all of the techniques should be evaluated in terms of the ability to meet the needs for radars aimed at the different users. Questions arise in processor design, particularly for hybrid systems, regarding where and how to do motion compensation, where and how to do range "dechirping," and where and how to do "azimuth dechirping." To obtain the answers to these questions, a detailed study of the techniques available at any particular time in the development of component technology will be required.

Processors tend to be subdivided into range-gated processors, which treat each range element separately for generating the azimuth resolution, and range sequential (usually range offset) processors, which process range elements one at a time but do not separate them until after the azimuth processing has been done. Both systems have advantages and disadvantages. Some of the earliest processors were range sequential, but development of digital techniques caused a trend toward range-gated processors and most of the current electronic processors are range gated. Recent developments in analog storage techniques (CCD and serial analog memory (SAM)) have again focused interest on range sequential processing; and in the process of reexamining this old technique, it has become apparent that digital implementations of range sequential processing may also be desirable. The processor types outlined in the following two subsections have been grouped into these two classes.

The types of processor that might be considered include those listed; but, no doubt, both new techniques and variations of the listed ones will be forthcoming in the next few years.

Range-gated processors: The range-gated processors under consideration are as follows.

1. Unfocused integration processor - For most applications, the use of focused processing is required to achieve adequate resolution; but for

some, unfocused processing - which is inherently simpler to accomplish - is sufficient. A single-look unfocused processor using this technique is shown in figure 5-10. Implementation for multiple looks requires using a separate LO for each look and duplicating the structure shown. The outputs must then be combined before they are made into an image.

2. FFT processor - The FFT algorithms enable filtering with minimum hardware for applications of the kind in space imaging radar. Special-purpose FFT processors for filtering are becoming part of various instruments used in the laboratory, and the same techniques can be and have been applied to SAR data processing. The FFT processor can be used for both range and azimuth dechirping, but here it will be assumed that the range dechirping has been accomplished elsewhere, probably with an analog, SAW device. The next step in the FFT processor is converting the chirped-signal returns into constant-frequency returns; this conversion may be accomplished in an analog fashion by mixing with a chirped LO (as shown), and in a digital fashion by performing the same operation digitally. An FFT processor is shown in figure 5-11. Note that the signal is first heterodyned down to a zero-frequency i.f. and that this transition requires I (in-phase) and Q (quadrature) channels. This technique seems to be preferred at present, but heterodyning to an "azimuth-offset" i.f. at $PRF/4$ is also possible, in which case the FFT operates at a higher rate but requires only one channel.

3. Correlation processor - A technique that has been used successfully in several organizations for processing images involves the correlation of the returned signal with a reference signal that is a replica of the signal from a point scatterer at the desired image point. This technique is diagrammed in figure 5-12. It, too, is usually used with I and Q channels but could be done with an azimuth offset and a single longer channel.

4. CCD-SAW analog azimuth processor - A processor using a CCD special chip for "corner-turning" memory and a SAW frequency-sensitive delay line for azimuth dechirping has been built for other purposes at the Royal Signals and Radar Establishment in England, and the SAW line has been used for these purposes at Rockwell International. This processor has great promise for modest-resolution SAR data onboard processing because of its small size and low power consumption. Such a processor is diagrammed in figure 5-13.

Serial synthetic aperture radar (SAR) processors: The serial SAR processors under consideration are as follows.

1. Unfocused recirculating processor - The early unfocused radars used a recirculating bulk-acoustic-wave delay line for processing. Today, this technique still appears applicable, but sampled-data devices such as CCD's and SAM's appear more suitable because of instabilities in the delay of the analog delay line caused by temperature. This technique could also be implemented by using digital shift registers. The method is very simple. A sketch of its architecture is shown in figure 5-14.

2. Comb-filter focused processor - The frequency response of a filter consisting of a recirculating delay line is a comb of responses,

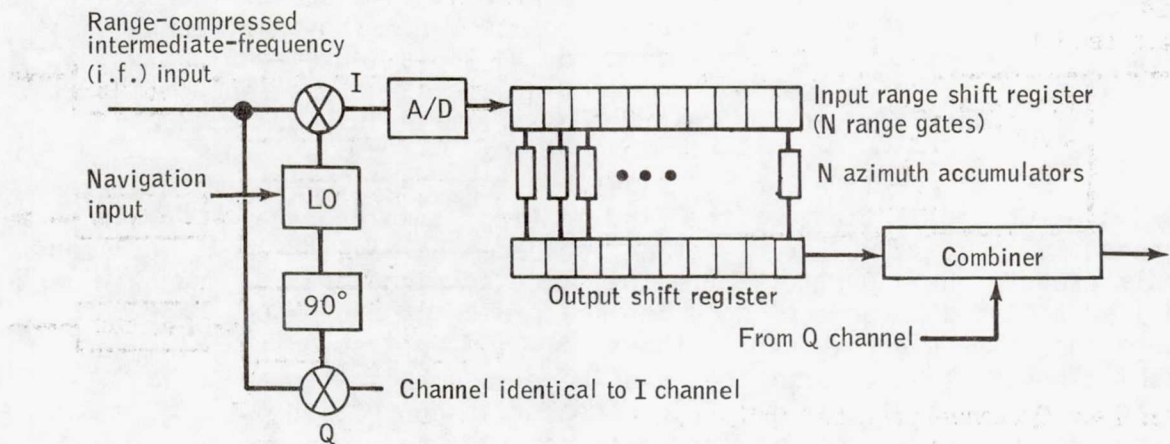
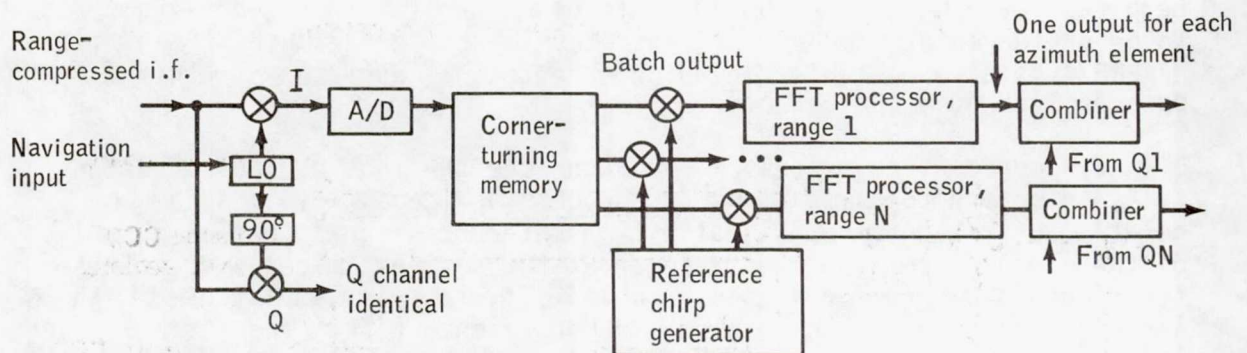


Figure 5-10.- Basic unfocused integration processor.



Note: I and Q channels may be replaced by single complex channel with I mixer providing real components and Q mixer providing imaginary components.

Figure 5-11.- Basic FFT processor.

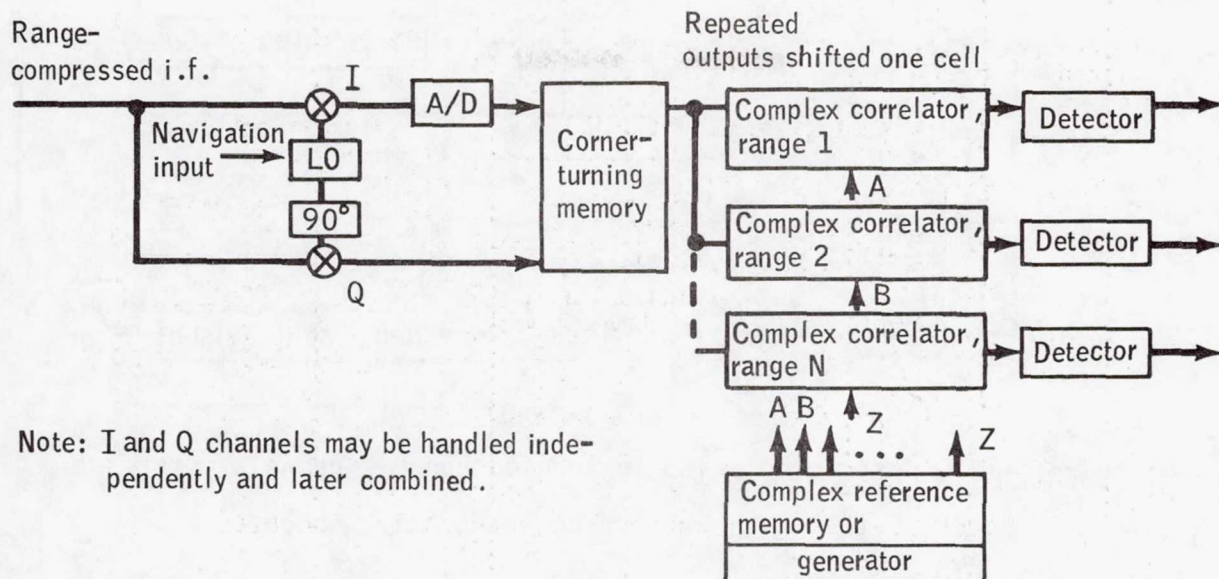


Figure 5-12.- Basic correlation processor.

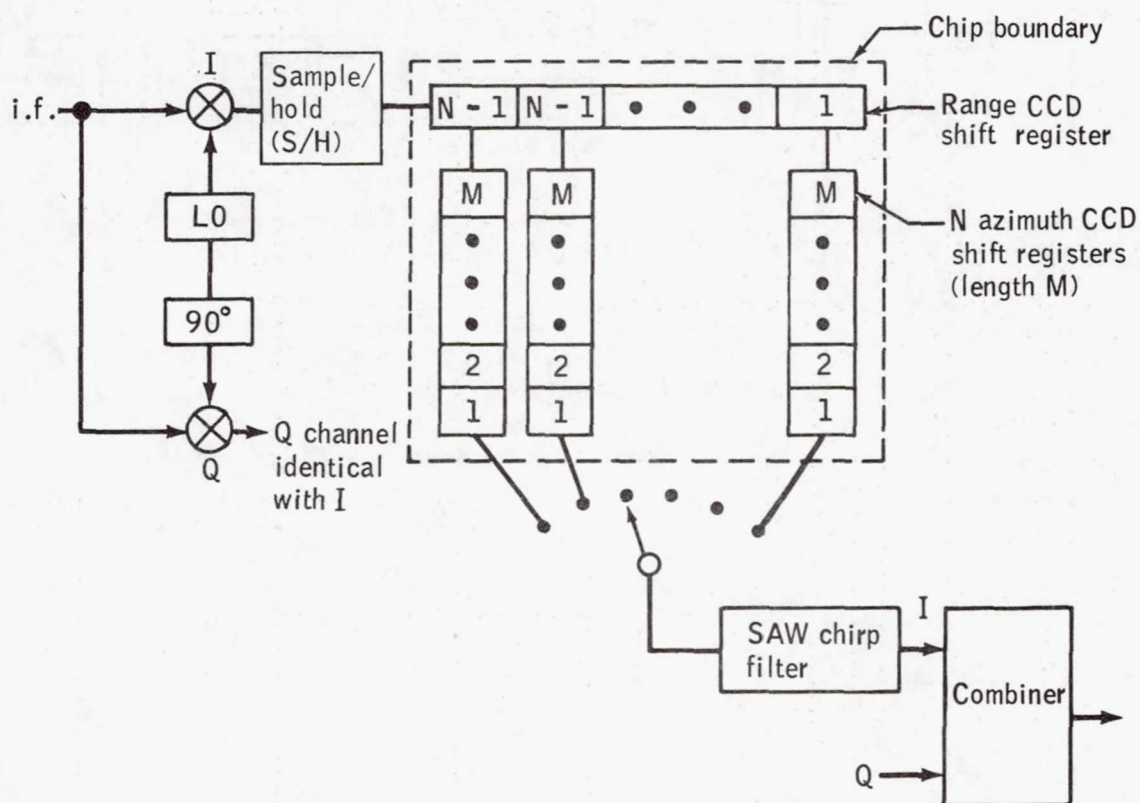


Figure 5-13.- CCD-SAW processor basic configuration - one look.

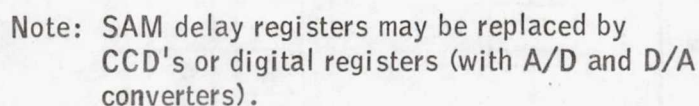
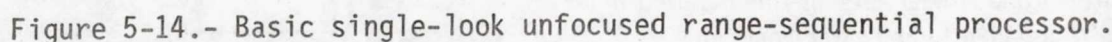


Figure 5-15.- Basic comb-filter range-sequential processor.

with each tooth centered about a multiple of the PRF. When a frequency-independent phase shift is introduced into the feedback loop of the delay line (or delay shift register), the teeth of the comb shift somewhat in frequency. Thus, a series of comb filters can select out of a return pulse a series of returns corresponding to different Doppler offset frequencies and therefore to different azimuth elements. Such a comb filter can be used in two ways in SAR data processing: (1) with fixed phase shift and a sweep LO preceding the comb filter to convert all received azimuth signals to fixed offsets as in the FFT processor or (2) with a variable phase shift permitting sweeping the comb filter response to follow the changing Doppler shift from a given azimuth position. A processor of the first type is shown in figure 5-15.

3. True synthetic aperture processor - A recent proposal by Texas Instruments, Inc., and the JPL is for a "true SAR" processor using analog implementations with CCD memories. This system, like the CCD-SAW processor, seems to offer a great deal of promise in terms of minimizing the power and space requirements of an onboard processor. The configuration is diagrammed in figure 5-16. When the number of pulses required to be processed has arrived, all the CCD's are full. At that time, the outputs go through the range-walk correctors to the multipliers that apply the appropriate phase corrections for each point in the aperture. The output then is summed and appears range sequentially for each azimuth position.

This group of processor options offers considerable promise that optimum processors can be developed for both onboard and ground applications. Some are already available for aircraft radars, and others need preliminary testing. The entire group needs to be considered to examine the optimum configurations for the different applications, and development on the untested versions needs to be conducted to verify the predicted performance. Such a program should be ongoing, because the right choice with today's component state-of-the-art may not be right tomorrow. On the other hand, this very fact indicates that full-scale development of prototype space systems should be delayed until a mission is identified so that the best trade-off can be made as to the hardware availability at that time.

Large Ground-Based Synthetic Aperture Radar (SAR) Data Processing Architecture

Formulative studies for application of the SAR have illuminated the need to deploy radar sensors operating from L-band through X-band on platforms ranging from aircraft through various types of satellites. Application requirements such as wavelength, image resolution, viewing geometry, and surveillance area differ significantly as a function of the application objectives and physics; and during the initial radar programs, optimum selection of these requirements will not be conclusively established. Many of the experimental programs will be intensive but short-duration efforts, with requirements to reduce acquired data through signal processes with variable parameter sets so as to develop relative sensor performance data comparisons.

The processing load for SAR data is of such magnitude as to preclude the application of conventional computation centers. It would be economically unrealistic to plan on handling sufficient data quantity to be statistically significant even during the experimental phases of radar application programs. If the optimum processing parameters were known and accepted within the community, practical special processors could be implemented with technology available today. However, this assumption is not valid, and such an approach would not be supportive of the experimental nature characteristic of early sensor application development.

These factors lead to the conclusion that flexibility rather than efficiency is the consideration that drives the architecture of a dedicated large ground-based SAR-data-processing facility. The architecture should initially support the experimental type of sensor programs, with the potential to be subsequently expanded to production processing of SAR image products to a format directly useful to the user community. A desirable but secondary consideration is the possibility of supporting advanced-technology processor development programs by providing simulation capabilities to emulate candidate specialized processor designs and to support input data generation and output data analysis during specialized hardware test activities.

Fortunately, there is a thread of commonality in SAR data processing across the many facility applications. The previous section on the operations required to produce SAR imagery illustrates this continuity. Algorithm options were found to be influenced by processor implementation technology selection more than by image application considerations. Existing processors for SAR or other intensive signal-processing applications illustrate the practicality of implementing the arithmetic functions as special dedicated processor modules or as programmable processor modules (e.g., the Hughes Aircraft Company's programmable signal processor built for the Air Force's forward-looking advanced multimode radar (FLAMR) program). The cost, size, power, and architectural selection of these processors have been controlled by memory technology considerations, and this trend is expected to continue.

A rational approach to the architecture of a large ground-based SAR-data-processing facility is to concentrate on the efficient but flexible utilization of memory available at the time of facility implementation. The SAR data are block oriented, and thus mechanical storage devices such as disks and drums would only be applicable if considerable process slowdown can be tolerated. This selection may be suitable as an interim facility step during the development of radar image applications, but the ultimate facility must have massive block-oriented solid-state data memory devices to support in a practical manner routine application image production. Because the relative size of internal SAR data buffers is dependent on the parameters for the specific application, this memory should be programmably allocatable to the different buffers through the use of a programmable storage controller. Provisions for efficient and convenient "corner turning" should be included as a hardware capability in this storage controller. Such a memory complex would provide the nucleus of a flexible processing facility, around which input/output (I/O) devices and programmable arithmetic processors could be coupled.

A system for ground-based SAR data processing extends beyond the hardware. Function, operational procedures, and (if programmable) software management must also be considered during the large ground-based SAR-data-processing architecture concept formulation. In the following paragraphs, key factors in these areas are tabulated. Principal issues that must be resolved before specifications are generated for the facility are also included.

Figure 5-17 shows a typical configuration for a large ground-based SAR-data-processing facility. The inputs required to operate such a facility are as follows.

1. Recorded sensor data
2. Platform motion data
3. Input data management parameters
4. Desired process parameters

The processing functions that such a facility must perform are as follows.

1. Data reading
2. Data editing and AGC correction
3. Pulse compression
4. Range-walk correction
5. Azimuth prefiltering
6. Clutter centroid estimation
7. Range-curvature correction
8. Azimuth compression
9. Pixel registration correction
10. Detection
11. Look averaging
12. Standard map projection
13. Image writing
14. Film copy preparation
15. CCT preparation

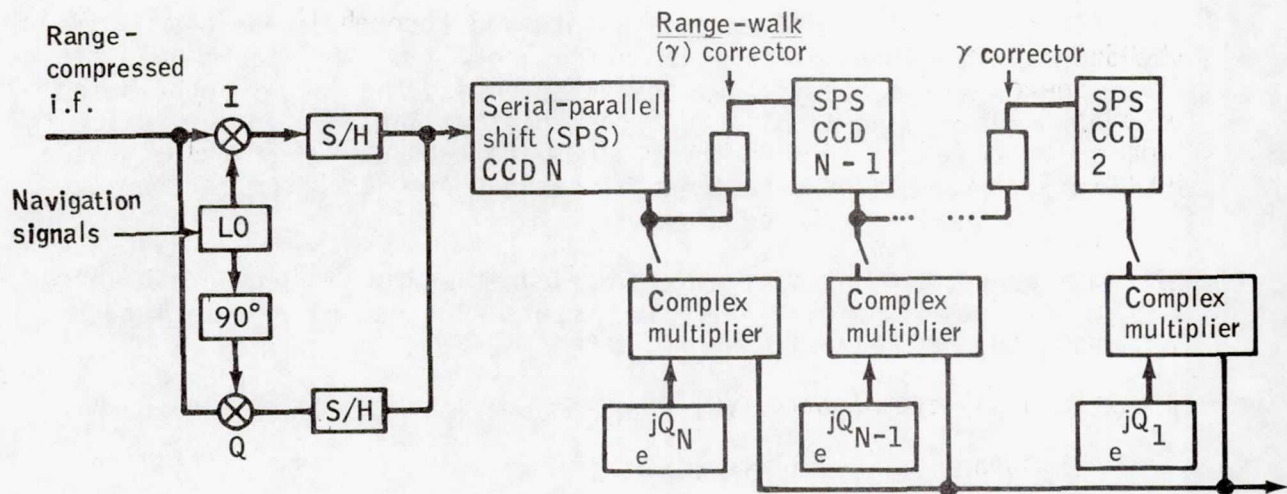


Figure 5-16.- Basic CCD true-synthetic-aperture processor.

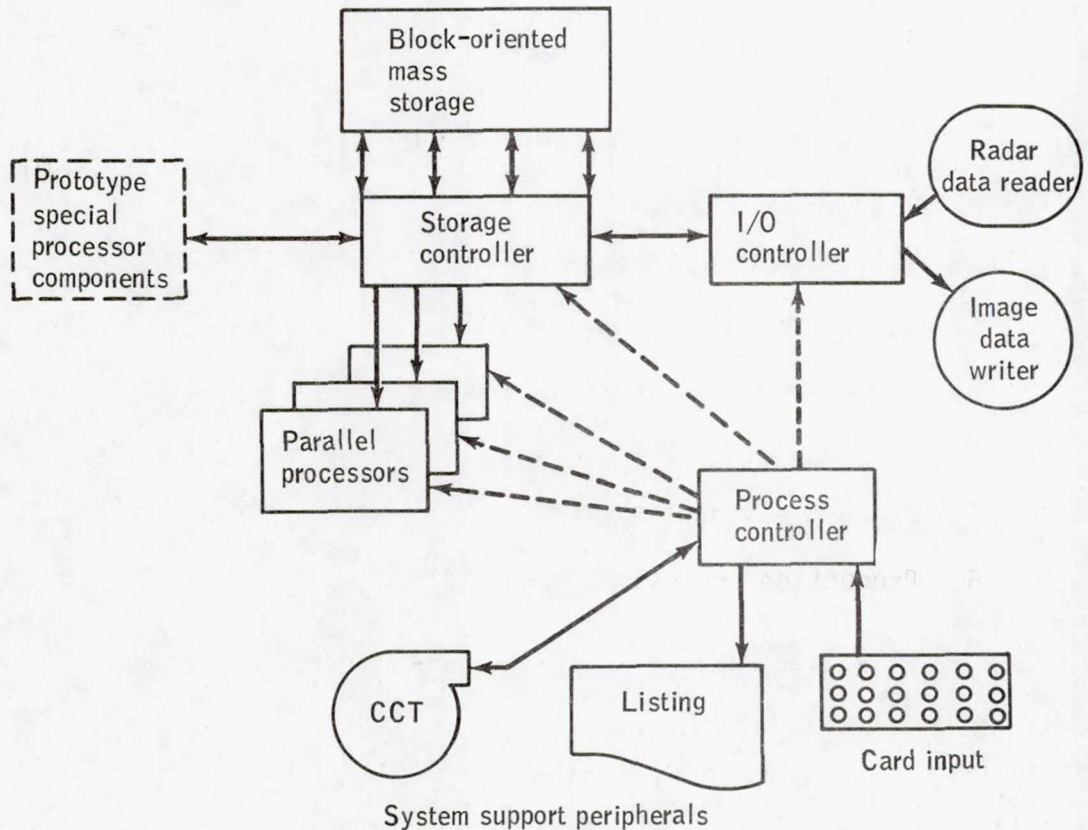


Figure 5-17.- SAR processor configuration.

Figure 5-18 illustrates how functions 13 through 15 are organized in the Seasat image formation processor currently under procurement by the JPL. There, the primary output is imagery on film, with secondary outputs of quantitative data for specific requirements available in CCT form. A comprehensive data-editing capability is necessary to select the data to be output in CCT form.

Extensive software will be required to implement a large ground-based SAR data processor. This software will include the following components.

1. SAR signal processing function library
2. High level control process assembler
3. Data library management programs
4. Control processor supervisor
5. Tape I/O support modules
6. CCT formatters
7. Diagnostic routines
8. Process configuration test data generator

Operation of a large SAR-data-processing facility will require the following elements.

1. Data library retention strategy
2. Machine readable tape identification and multitape linkage
3. Process configuration management and documentation
4. Standardized I/O formats
5. Process validation standards
6. Production process work sheets

Analog-to-Digital Quantization Precision Requirements

An A/D converter may be modeled as shown in figure 5-19. This figure consists of a box of unity transfer function plus a noise generator. The block diagram and the noise power level are given by W. Bennett (ref. 5-14). The noise power, N_q , added by the quantizer is shown by Bennett to be

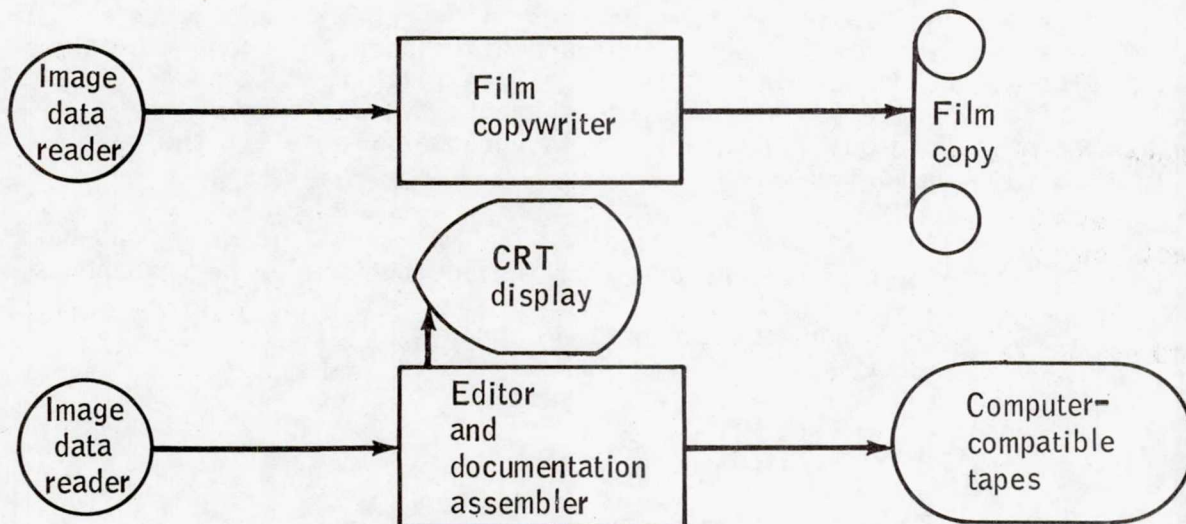


Figure 5-18.- Seasat product generation.

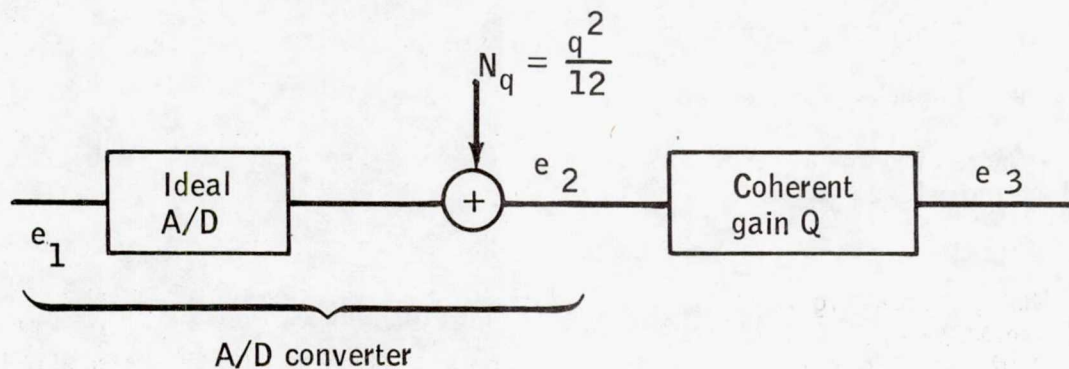


Figure 5-19.- Model of A/D converter.

$$N_q = \frac{q^2}{12} \quad (5-20)$$

where q is the least count of the A/D converter.

Let Q be the coherent gain between the A/D converter and the final radar output.

The power level at point 1 in figure 5-19 is S_1 and N_1 for signal and noise, respectively. These levels become

$$\left. \begin{aligned} S_2 &= S_1 \\ N_2 &= N_1 + N_q \end{aligned} \right\} \quad (5-21)$$

at point 2.

At the radar output, one has

$$\left. \begin{aligned} S_3 &= Q^2 S_1 \\ N_3 &= Q(N_1 + N_q) \end{aligned} \right\} \quad (5-22)$$

Hence,

$$\frac{S_3}{N_3} = \frac{QS_1}{N_1 + N_q} \quad (5-23)$$

Next, the assignment of the number of bits in the A/D converter needs to be considered. Following Bennett, proceed as follows: Let n_b be the number of bits in the A/D converter. Because bipolar signals are to be converted, assign $n_b - 1$ bits to the maximum amplitude of each polarity. Let $n_b - 3$ bits be assigned to the signal-plus-noise standard deviation (σ) at point 1, the converter input. Thus, full amplitude of the A/D converter corresponds to the $4\text{-}\sigma$ value, and the probability that signal plus noise at point 1 will exceed the A/D converter dynamic range is very small. The assignment of $n_b - 3$ bits to the standard deviation is written as

$$2^{n_b-3} q = \sqrt{S_1 + N_1} \quad (5-24)$$

Combining equations (5-20) and (5-24) gives, on elimination of q ,

$$N_q = \frac{S_1 + N_1}{12(4^{n_b-3})} = \epsilon N_1 \quad (5-25)$$

The value for ϵ makes N_q equal to some acceptable multiple of N_1 .

Use of equation (5-25) in (5-23) gives

$$\frac{S_3}{N_3} = \frac{Q}{1 + \epsilon} \frac{S_1}{N_1} \quad (5-26)$$

Some minimum value for S_3/N_3 at the output is usually required. Hence, S_3/N_3 has a given value. Some value exists for S_1/N_1 at point 1. The system coherent gain Q can be computed with knowledge of the pulse compression and azimuth compression ratios. Hence, ϵ can be computed. From equation (5-25), the number of bits, n_b , in the A/D converter can be found from

$$2^{2(n_b-3)} = \frac{S_1 + N_1}{12\epsilon N_1} \quad (5-27)$$

Hence,

$$2(n_b - 3) = \log_2 \left(\frac{S_1 + N_1}{12\epsilon N_1} \right) \quad (5-28)$$

or

$$n_b = 2 - \log_2 \sqrt{3} + \log_2 \sqrt{1 + \frac{S_1}{N_1}} - \log_2 \sqrt{\epsilon} \quad (5-29)$$

If ϵ is chosen so that the extra noise due to the A/D converter is small - e.g.,

$$\epsilon = \frac{1}{12}$$

then

$$n_b = 3 + \log_2 \sqrt{1 + \frac{S_1}{N_1}} \quad (5-30)$$

If the noise due to the A/D converter is allowed to equal the input noise (e.g., $\epsilon = 1$), then

$$n_b = 2 - \log_2 \sqrt{3} + \log_2 \sqrt{1 + \frac{S_1}{N_1}} \quad (5-31)$$

Thus, the number of bits required to place the quantization noise between the units of 1/12 and 1 times the input noise is between the values given by equations (5-30) and (5-31).

In addition to controlling quantization (and saturation) noise, another important consideration in the specification of A/D converter precision is A/D gain variation as a function of input signal level (small signal suppression).

Input Data Requirements

The SAR sensor differs considerably from the visual and IR sensors in both the form of input data and the processing required to obtain a usable image product. The principal differences will be described, and the essential input data components required to produce quality imagery will be identified.

Transmitted signal.- The SAR is an active imaging system in which the ground is illuminated by energy transmitted from the vehicle. The short pulses required to provide high range resolution are difficult to achieve because of technological difficulties of implementing the high peak power necessary to provide sufficient illumination energy in a short time. Today's radars overcome this limitation by transmitting a lengthened pulse of lower peak power that is frequency coded to permit subsequent pulse compression after return reception. For the radar to function properly, the following information must be known about the transmitted signal.

1. Transmitted waveform to establish effective carrier frequency and to permit pulse compression
2. Average pulse power for calibration
3. Pulse transmission time to reference range measurement (clock reference, PRF, and pulse count)

The transmitted waveform is extremely stable and needs only to be checked or updated every month. The pulse power is less stable and should be updated approximately once per hour. The pulse transmission time must be current; however, the PRF is traditionally derived from extremely stable clocks, and thus the transmission time is inherent in the pulse count. When range gating and sampling are derived from this same clock, time synchronization needs to be accomplished only upon system initialization and about once a day. Pulse count must be available for any block of input data.

Received radar data - The received radar data are characterized by amplitude and phase as a function of time relative to the epoch of the transmitted signal. The received-data bandwidth is limited by the response characteristics of the receiver so as to reject interference and noise outside the spectral window of the radar. Because the nominal signal strength can vary considerably as a function of range because of the $1/R^4$ term in the radar equation, a gain function (sensitivity versus time control or STC) is applied as a function of time to equalize the power level that must be accommodated by the data acquisition system components. The gain function is usually a prestored function modified by a slowly varying multiplier that adapts to the observed received-data power history. This gain function must be accounted for to retain an

image calibration. Amplitude and phase data can be represented either as real and complex components at baseband (zero frequency for the i.f.) or as only the real component of data that has been offset in frequency so as to preclude interpretation ambiguity. If these data are sampled, they must be observed at a rate greater than two observations (one complex observation) per hertz of significant power bandwidth. These samples are usually acquired over only the fraction of received time that corresponds to surveillance ranges of interest.

In summary, the following information must be known about the received signal.

1. Video data (complex or real with offset value)
2. Video data time relative to pulse transmission (range gate reference, sample rate, and sample count)
3. STC function
4. AGC parameter

Video is the bulk of SAR data and must be collected with the dynamic range identified in the preceding sections. The range window reference and gain control parameter should be known for each pulse. The sample rate and STC functions are usually a constant for a particular system.

Precision vehicle navigation. - To form a synthetic radar aperture, the motion of some vehicle is used to translate the real antenna through space during an interval of time. During this interval of time, the antenna position must be known to a small fraction of a wavelength. The vehicle acceleration vector must be measured or otherwise known to achieve this result (acceleration can be calculated for satellite platforms). When the acceleration reference point (vehicle center-of-mass) is not at the antenna focal point, vehicle attitude histories and the antenna/acceleration reference point geometry must be known. In summary, the information needed is as follows.

1. Antenna/vehicle geometry
2. Vehicle attitude
3. Precision vehicle position (reference velocity and acceleration)

The quality of these data must be sufficient to allow one to estimate the relative vehicle position during the aperture time to within a small fraction (less than one-eighth) of a wavelength. For the L-band, this length is on the order of a centimeter. Higher radar frequencies require even more precision.

Vehicle/terrain geometry. - An SAR basically creates images in range and subtended angle relative to the average velocity vector during the synthetic aperture time period. These coordinates are derived from round-trip travel time and the observed Doppler history, and not from the real-antenna orientation. This distinction is a significant and often

misunderstood difference between SAR and optical imagery. Knowledge of the terrain geometry relative to the vehicle is necessary to resolve the third coordinate variable. Thus, vehicle position affects more than just the registration of image data on a reference grid system. In summary, the information needed is as follows.

1. Vehicle position (to accuracy of uncorrected registration requirement)
2. Vehicle velocity vector (to accuracy of uncorrected image registration requirement at end of range arm)
3. Terrain relief (to accuracy necessary to register the map in range)

Antenna pattern projection.- Knowledge of the terrain projection of the antenna pattern is required to interpret the Doppler spectrum properly during the image processing and to correct shading caused by the real antenna for purposes of retaining image calibration. Note that the radar image registration is not affected by the antenna attitude. Thus, the attitude control of the sensor platform is significantly relaxed from that of the optical sensors. In summary, the parameters of importance are as follows.

1. Antenna pattern (antenna size and shading)
2. Antenna attitude (one-fiftieth of beamwidth)

Data management.- Because of the mass of SAR data, special considerations should be given to data management. The following conclusions are based on experience with other mass data systems.

1. The parameters and histories necessary for processing should be contained within the input data record format.
2. Contiguous data tapes should be unambiguously linked by header and trailer information.
3. Data library maintenance should be automated.

IMPLEMENTATION TECHNOLOGY

The Implementation Technology Subpanel was supplied with the following questions/instruction to guide its work.

1. What are the comparative merits of digital versus analog processing?
2. How should the radar data be recorded in the Shuttle? Contrast optical versus magnetic tape recording.

3. What hardware and technology developments are needed in the immediate future to allow realization of a fully digital SAR-data-processing system?
4. What memory technology is best suited for implementing an all-digital SAR data ground-processing facility?
5. How should processing be partitioned between in-flight and ground processing?
6. How should the processor output image be recorded?
7. What are the capabilities of existing SAR-data-processing systems?

A Comparison of Various Analog and Digital Techniques for Synthetic Aperture Radar (SAR) Data Processing

There are a number of analog and digital techniques that can be and have been used in SAR systems. There also are a number of hybrid systems in which a combination of analog and digital techniques is used. It is the purpose of this subsection to compare some of these systems with respect to complexity, speed of operation, cost, power requirements, etc.

The major analog system (and one of the earliest) is optical processing. In this type of system, use is made of the fact that linearly frequency modulated signals have self-focusing properties and that both chirp and synthetic aperture signals are of this form. In general, the focal lengths of the signals have inconvenient values, and telescopic, anamorphic lens systems are used to process these signals.

With such optical systems, the pulse compression and azimuth compression can be performed simultaneously. Moreover, storage on a film as dense as 40 to 100 lines/mm can be achieved, with a maximum dynamic range of approximately 25 dB at each such point. This accommodation is equivalent to a storage capability of approximately 1.6 megabits/cm² (10⁷ bits/in²).

The disadvantages of optical processing are mainly due to the necessity to use silver halide film as a storage medium. The use of chemicals is required to develop the film; and unless extreme care is used, a variation in the density achieved on the film is obtained.

Because the optical processing system is an analog device, one can expect an accuracy or repeatability of not over 0.1 percent.

Another problem is that of time delay. Two films, the signal history film and the output image film, must be developed. This process is, at the minimum, several minutes in duration.

Another problem with using film as the data storage medium in optical processing is that of film length in the developing stations. The finer the resolution on the film, the longer the distance along the flightpath that corresponds to that length of film. Thus, the vehicle may have gone

a long distance before the film is available for exploitation of the image.

Although alternatives to silver halide film recording exist, they have not to date been too successful, largely because of the high level of energy required to expose them compared to that required for silver halide film.

Digital techniques can be used to perform both the pulse compression and azimuth compression in SAR's. Convolutional processing and its equivalent in FFT processing are appropriately implemented with the use of digital techniques.

In some cases, however, the data rate required becomes extreme. For example, Seasat has a swath width, W , of 100 km, with a range resolution, ρ_r , of 25 m; this combination corresponds to 4000 range elements.

At a speed V of approximately 8000 m/sec, in 10 minutes the number of azimuth elements passed over is

$$\frac{Vt}{\rho_a} \approx 2 \times 10^5$$

where ρ_a is the azimuth resolution. Thus, approximately 8×10^8 points are viewed for each 10-minute pass.

After presumming, a minimum of V/ρ_a complex data points must be stored per range bin per second. For a dual-frequency dual-polarized system with a quantization precision of five bits, the total data storage required to record a 10-minute pass can be calculated from

$$N_b = \frac{2Vn_b n_f n_p W t}{\rho_a \rho_r} = 30.7 \times 10^9 \text{ bits} \quad (5-32)$$

where n_f is the number of system frequencies on which maps are to be formed, n_p is the number of polarizations, V is the platform velocity, n_b is the number of A/D bits used, W is the swath width, and t is the time.

Digital tape recorders can achieve approximately 7.9×10^3 spots/cm (20×10^3 spots/in) along the track, and 100 tracks across a 5.1-cm-wide (2 in. wide) tape. The density of spots on the tape is thus approximately 155.0×10^3 spots/cm² (10^6 spots/in²). The area of digital magnetic tape required to store a 10-minute Seasat pass is thus $[N_b/(1550 \times 10^6)] \text{ m}^2 = 19.8 \text{ m}^2$ ($(N_b/10^6) \text{ in}^2 = 30.7 \times 10^3 \text{ in}^2$). For 5.1-cm-wide (2 in. wide) tape, this area requires a tape length of 390.1 m (1280 ft). Approximately 1828.8 m (6000 ft) of 5.1-cm-wide (2 in. wide) tape are required to record the data prior to presumming. The minimum tape speed required to keep up with the Seasat data rate in real time is thus 1828.8 m/600 sec or 3.0 m/sec (6000 ft/600 sec or 10 ft/sec (120 in/sec)).

The spot density of 155.0×10^3 spots/cm² (10^6 spots/in²) for magnetic tape is approximately equal to the spot density for silver halide

film. If used digitally, the tape stores one bit on such a spot; if used in analog fashion, perhaps five or six bits per spot can be shared. Thus, the area of magnetic film is about equal to that of silver halide film if the magnetic tape is used to store an analog signal. If the tape is used to record a digital signal, then magnetic tape requires five or six times more area than does film (with analog storage). Of course, if digital data are stored on film, the film area required will be about the same as that used by magnetic tape in recording digital signals.

Alternatives (hybrid analog-digital techniques) exist in newer technologies such as the use of CCD's and bubble memory techniques. In these cases, it is possible to arrange architectures that greatly reduce the equipment and time required to perform the computations. The equipment can be configured to do both pulse compression and azimuth compression efficiently. Its state of development is not as far along as that of either the pure optical or pure digital equipment. Its potential for the future, however, is very great.

There are other variants to both the optical and the digital processors. For the optical case, a technique known as polar format makes it possible to process the signal history film by using a two-dimensional Fourier transform. There is, of course, a digital equivalent.

In the digital case, there is an alternate generally known as batch processing. This alternate and the aforementioned polar format are pertinent to the case of mapping an area about some selected point. The processing is an approximation; but for batch processing, an FFT gives N image points, with N equal to the number of samples used in a synthetic aperture computation. Thus, the computation rate is reduced. However, the batch processing approximation is valid only over a limited region about the selected focus point. A sequence can be taken of selected focus points properly arranged in range and along track to fill in an extended region such as in the scansar concept proposed by the University of Kansas (ref. 5-15).

Various combinations not previously discussed exist. Optical recording does not necessarily imply optical processing. One can record either analog or digital signals on film. The subsequent processing can either be optical or digital.

Similarly, the pulse compression can be done either by analog or digital means. The SAW devices are an excellent means for pulse compression. These devices do not limit the choice of how the azimuth compression is performed.

Time-Domain Filters

In the time-domain filtering technique, small SAW delay lines are used to perform chirp transforms for rapid, narrow-band signal processing. The time-domain filter (TDF) is so called because it forms dispersed and resolvable time waveforms in response to monochromatic signal tones having different frequencies. This dispersal in time results from the Fourier transform properties of pulse compression/expansion delay lines. The TDF

is suitable for any processing system that requires narrow-band filtering, particularly if the processing-speed requirements are high. These devices have been used successfully in medium- and low-PRF-pulse Doppler and SAR systems. Because of its small size and weight and low power consumption, the TDF is well suited for missile and spaceborne radar applications and provides an attractive alternative to digital DFT mechanizations.

The key element of the TDF is the passive SAW delay line. These devices are constructed by deposition of metallic interdigital fingers (transducers) on a piezoelectric substrate. Lithium niobate and ST-quartz are common substrate materials. Well-controlled amplitude and phase responses are achieved by using highly accurate masks prepared by automated plotting equipment. Because of its simplicity and the fact that it contains no active elements, the SAW line offers a low-cost and highly reliable means of implementing high-speed, real-time filters.

Rockwell International has built and tested a number of TDF's for various radar applications. As an example, one of these devices performs the equivalent of a 64-point DFT in 8.5 seconds. This particular unit is contained on a 16.5- by 19.1-cm (6.5 by 7.5 in.) circuit board, weighs 0.54 kg (19 oz), and dissipates 5.5 W.

When the TDF is used in a sampled-data application such as azimuth correlation in an SAR, the required time-bandwidth product of the SAW lines is equal to the number of radar pulses to be correlated. Time-bandwidth products of several hundred can be achieved with SAW lines by using simple, conventional surface-wave structures. The conventional SAW devices are limited to bandwidths of less than 100 MHz and time delays (processing intervals) of less than 60 microseconds.

To illustrate the use of a TDF for SAR imaging, consider an application wherein the data rate is 25 MHz and the azimuth resolution improvement or number of azimuth samples to be correlated is 150. The bandwidth of the SAW lines is established by the input signal bandwidth, which is 25 MHz in this example, and the length of the lines would be $150/(25 \text{ MHz})$ or 6 microseconds. These parameters are well within the capability of conventional SAW lines.

A total of $2(150)\log_2 150$ or approximately 2000 multiplications would be required to perform this same function with an FFT processor. To accomplish the FFT in 6 microseconds, multiplications would have to be performed at an average rate of one per 3 nanoseconds. With present hardware technology, the digital multipliers required to implement the FFT can perform a multiplication in no less than approximately 50 nanoseconds. The TDF for this application can be contained on approximately 322.6 cm^2 (50 in^2) of circuit board.

Unlike DFT's, the TDF has a continuous output as a function of frequency. This characteristic enables sampling of the signal spectrum at frequency intervals less than the reciprocal of the observation time. Oversampling in the frequency domain reduces the effects of filter or range straddle such as reduced signal-to-noise ratio and distortions that degrade image quality.

Azimuth or range sidelobes may be reduced in the TDF by conventional amplitude weighting. Sidelobes of better than -40 dB have been achieved except at very low delay line time-bandwidth products.

Practical TDF's generally have dynamic ranges of from 40 to 50 dB. The SAW lines themselves have dynamic ranges in excess of 60 dB; however, the overall filter performance is degraded by noise generated in and picked up by peripheral electronic circuits.

Rationale for Data Recording in the Shuttle Imaging Radar

Whether Shuttle SAR data will be recorded or transmitted in real time will depend largely on the Shuttle mission purpose and the capability of the NASA tracking and data relay satellite system (TDRSS).

The purpose of the SIR is to support user requirements for radar imagery. It will, however, be a research and development tool that should be very flexible, with a capability for configuration changes as radar parameters become better defined and as mission requirements change. It will be used to define later free-flyer SAR instruments. It also may eventually be used as a quasi-operational Shuttle instrument, responding to emergency requests for radar data, and could eventually become a part of a space station. Near term, it will, however, be a development tool.

This means that, initially, the SAR data are not time critical; the 1-week delay (which corresponds to the Shuttle mission length) should provide no real problems. It also means that, initially, data volume and rates will be at a maximum; i.e., 280 to 350 Mbps. (Until parameters are better defined, there is a reluctance to do too much processing on board.)

In the time frame of Shuttle SAR's, the TDRSS will be the principal means of communication between Earth-orbiting satellites and the ground. The maximum rate of data relay by the TDRSS is 300 Mbps, less than the 350 Mbps desired for the SIR. Furthermore, if the SIR data rate exceeds 30 Mbps, it must provide its own link with the TDRSS. (The Shuttle relay link data rate is only 30 Mbps.) This specification implies (1) implementation of a relay link, (2) more onboard processing, or (3) provision of recorders.

Because time will not initially be critical and it is desirable to maximize flexibility, recorders are initially the best alternative. As development progresses and parameters become better defined, more onboard processing (such as presumming) could be incorporated to reduce the 350 Mbps of data to a more reasonable quantity of information. Later configurations should include the capability to transmit real-time data for at least one channel (for emergency support).

The previous paragraph implies that, at least for early flights, a recording capability is needed. The type of capability is dependent on the ground system and the purpose of the flight. The real technical trade-offs have been previously discussed. In the following paragraphs, however, some operational considerations are presented.

Either optical or digital recording would be workable in the Shuttle mode of operation. More experience has been obtained in the optical area, and hence this technique might be more readily implementable. It also may be more apropos for establishing an onboard quick-look display capability.

However, some accuracy and flexibility are sacrificed. Also, as the SIR is presently configured, new recorder capability, even in the optical area, must be developed. (The technology is there but must be reconfigured.) In an ERIM study done for the JSC, this required development was a significant cost item in the data system.

Furthermore, film would not be acceptable for free-flyer or space station designs growing out of the SIR flights because it would not be retrievable. Also, it would not be apropos for the "record → slow down → transmit" mode of using direct transmission to the ground for "emergency support." Therefore, because (1) development will be required either way, (2) future operational modes are more compatible with digital recording, and (3) maximum accuracy and flexibility are obtained with digital recording, the recommendation is to plan to use digital recording at this time.

Required Hardware and Technology Development

The technology exists today for a fully digital SAR-data-processing system - on the assumption of four-bit encoding of radar video. For five-bit or more encoding, advances in digital-tape-recording technology are required.

When CCD's and/or bubble memories mature, reliability and maintainability will be enhanced; and in addition, size and power requirements will be reduced.

A 100-megabit digital recorder using bubble domain memory elements is being developed by Rockwell International under contract to the NASA LaRC. The program monitor is Dr. Stermer. The recorder is space qualifiable and is scheduled for completion in early 1978. Characteristics of the recorder are listed in the following table.

<u>Parameter</u>	<u>Characteristics</u>
Memory organization	One 100-megabit memory or two 50-megabit memories or four 25-megabit memories
Input formats	Serial or parallel in eight-bit bytes
I/O rate	2.4 MHz or 1.2 MHz
Mean time between failures	40 000 hr
Volume	9832.2 cm ³ (600 in ³)
Power	100 W at 28 V (during write or read only)
Type of memory element	Nonvolatile bubble domain (memory held by permanent magnet)

NASA should continue support in developing the technology of magnetic tape recording and signal-processing elements with the use of CCD, SAW, and magnetic bubble techniques.

Preferred Memory Technologies

The preferred memory technologies for implementing an all-digital SAR data ground-processing facility are as follows: For recording the source data signal, high-density magnetic tape is the preferred technique. The corner-turning memory required is presently best implemented by using metallic oxide semiconductor (MOS) shift registers and random-access memories; but in the near future, CCD shift registers and bubble memories will be preferred. For non-real-time processing, large disk memories are preferred. The processed image data should be recorded on high-density, instrumentation-type color film.

Stages in the Development of Onboard Processors

At least three steps should be taken in the move toward onboard processing. Initially, such processing should be minimized. With data in their rawest form, there is maximum flexibility in defining engineering parameters. However, when SAR instrument calibration parameters have become more firm and the state-of-the-art in onboard processing has advanced, step 2 should be taken. This phase involves the implementation of onboard preprocessing of the Shuttle SAR data. This development should increase that facility's usefulness by decreasing data quantity. The TDRSS can be used or the recorders can be more appropriately used to store processed information rather than raw data.

The next step is the big one. As scientists begin to perfect SAR data analysis techniques, phase 3 should begin. This phase should correspond somewhat to the definition of special-purpose radar free-flyers whose characteristics have been determined by using the Shuttle SAR data. In these free-flyers, onboard processing should be expanded to include processing to an actual user-product form, data that have been corrected and possibly formed into a particular map projection, etc.

Ideally, there might be another step between steps 2 and 3 involving the implementation of a very flexible onboard processor in the Shuttle SAR system that could be programed to produce a variety of the aforementioned user products.

Capabilities of Existing Synthetic Aperture Radar (SAR) Data Processing Systems

Optical correlators.- Laboratory optical correlators at the Goodyear Aerospace Corporation, the ERIM, and the JPL all have similar capabilities; i.e., approximately a 5.1- by 5.1-cm (2 by 2 in.) aperture at the data plane. This size is sufficient to process a quarter swath of the proposed spaceborne SAR systems (Seasat/Shuttle X-band and L-band). Minor modifications to these processors are required to implement the range-curvature

and range-walk corrections required in the orbital case. In addition, if data have not been compensated for the Earth's rotation and antenna pointing, additional minor modifications are required to implement an optical clutter lock.

Digital processors.- Candidate digital processors for proposed spaceborne SAR systems are the SAPPHIRE and the Hughes Aircraft Company PSP. The SAPPHIRE equipment (built by the Goodyear Aerospace Corporation) has adequate storage (30 megabits) for processing one azimuth look of the L-band system and all four azimuth looks of the X-band system. Techniques and additional equipment are required to combine the azimuth looks (of the L-band system) on subsequent processing passes. Modifications to the range compression filter would be required to accommodate the larger range compression ratio (approximately a factor of 4) of the spaceborne systems. Processing could be provided at a real-time rate.

A data-processing system consisting of a Hughes Aircraft Company PSP as its central element could be constructed that would have the capability of processing Seasat-A data. At an approximate vehicle speed of 7500 m/sec and for 25-m azimuth resolution, data are collected at a rate that can produce 300 (7500/25) lines of imagery per second. Because the number of range cells across the swath is approximately 4000, approximately 1.2×10^6 pixels must be formed per second to keep up in real time. On the order of 100 arithmetic operations per pixel are required to produce imagery; therefore, 120×10^6 operations per second are required to keep up in real time. The types of arithmetic operations that are required in quantity (multiplication and addition/subtraction) are performed at a rate of 20×10^6 per second on the PSP. Therefore, as far as its arithmetic capability is concerned, the PSP could perform Seasat-A processing with a 6:1 slowdown. It is projected that approximately 10 minutes of data per day will be collected. Therefore, as much as a 144:1 slowdown in processing could be tolerated to keep abreast with data collection on a daily basis. The PSP thus has a considerable margin, in terms of arithmetic capability, with which to account for overhead, maintenance, and downtime, as well as allow for far more computations per pixel than estimated.

Another aspect of the throughput problem, however, is mass storage and the bandwidth of data transfer between the mass storage device and the processor. For Seasat-A, on the order of 4 million words or 50 million bits of storage are required to process 4 azimuth looks. A random-access memory of this size does not presently exist at the Hughes Aircraft Company. Because a significant slowdown in processing Seasat-A data does not prevent keeping abreast with data collection on a daily basis, a completely random access memory is not required. However, disk memory does not serve well because only a few reads and writes of each data point can slow processing so drastically that the amount collected daily could not be processed in a day. Some disk memory is probably needed; but in addition, a large amount of block-oriented random-access buffer memory would be needed to feed, in a timely manner from disk, the random-access memory from which arithmetic operations are performed. The structure of this memory needs to be studied. The memory architecture that turns out to be optimum for Seasat-A on a cost/image production basis will probably be suitable for future satellite applications as well.

The existing PSP processing facility at the Hughes Aircraft Company has presently approximately 1.2 million bits of memory. Seasat-A processing could be performed with this system at approximately a 1000:1 slowdown. The memory is expandable, and that feature would be a firm requirement for timely Seasat-A processing.

The ERIM has established a digital processing facility that is dedicated to the processing of SAR digital data. The facility is useful for two purposes: (1) the development of two-dimensional digital signal-processing techniques applied to SAR image formation and (2) the development of manual and automatic exploitation techniques that will improve the practicability of imaging radars in various applications. The facility comprises a minicomputer-based system of specialized hardware in a multi-user operating environment. The system has been specifically tailored for efficient SAR data processing and image exploitation.

A block diagram of the digital facility appears in figure 5-20. The basic component of the system is a Digital Equipment Corporation (DEC) PDP-11/45 central processing unit that utilizes 262 144 bytes of online memory through the use of memory management hardware. An advanced operating system (RSC-11D) allows multiple real-time tasks to run concurrently on the machine, with a single task addressing as many as 65 536 bytes of memory. Intertask communication is permitted, a capability implying that several tasks could potentially be working on a single processing problem. Several computer terminals are provided so that several users can use the facility simultaneously.

Special provisions have been made for offline storage. Because of the vast amounts of data associated with SAR phase histories or images, a 116-million-byte random-access disk unit has been included in addition to a DEC RK05 disk unit (2.4 million bytes) used for operating-system and user program storage. The magnetic tape system consists of two nine-track and one seven-track dual-density-type drives and allows tape-to-tape processing in formats compatible with virtually all industry standards except the newer 2460.6-bit/cm (6250 bit/in) format.

To aid in implementing SAR digital-processing algorithms, a hard-wired FFT processor has been included in the system. The FFT processor (Time Data, Inc. FPE4) can perform a 1024-point complex FFT in 200 milliseconds. The data frame size for the FFT is controllable from 4 complex points up to 4096 complex points in powers of 2. In addition to real and complex, direct and inverse transforms, the processor can perform frequency domain Hanning filtering, as well as automatic and cross-spectrum averaging. Software has been generated that enables use of the FFT processor to perform a large-array two-dimensional FFT (as many as 1024 by 1024 complex points).

An interactive digital image display has been integrated into the digital facility. The RAMTEK display, which has a solid-state shift register refresh memory, is capable of displaying digital imagery in two modes: (1) 512 by 512 by 6 bits on a black and white TV monitor and (2) 256 by 256 bits on a color TV monitor, with 6 bits each controlling the red, green, and blue intensities for each picture element. Overlay channels are provided so that graphical information such as object

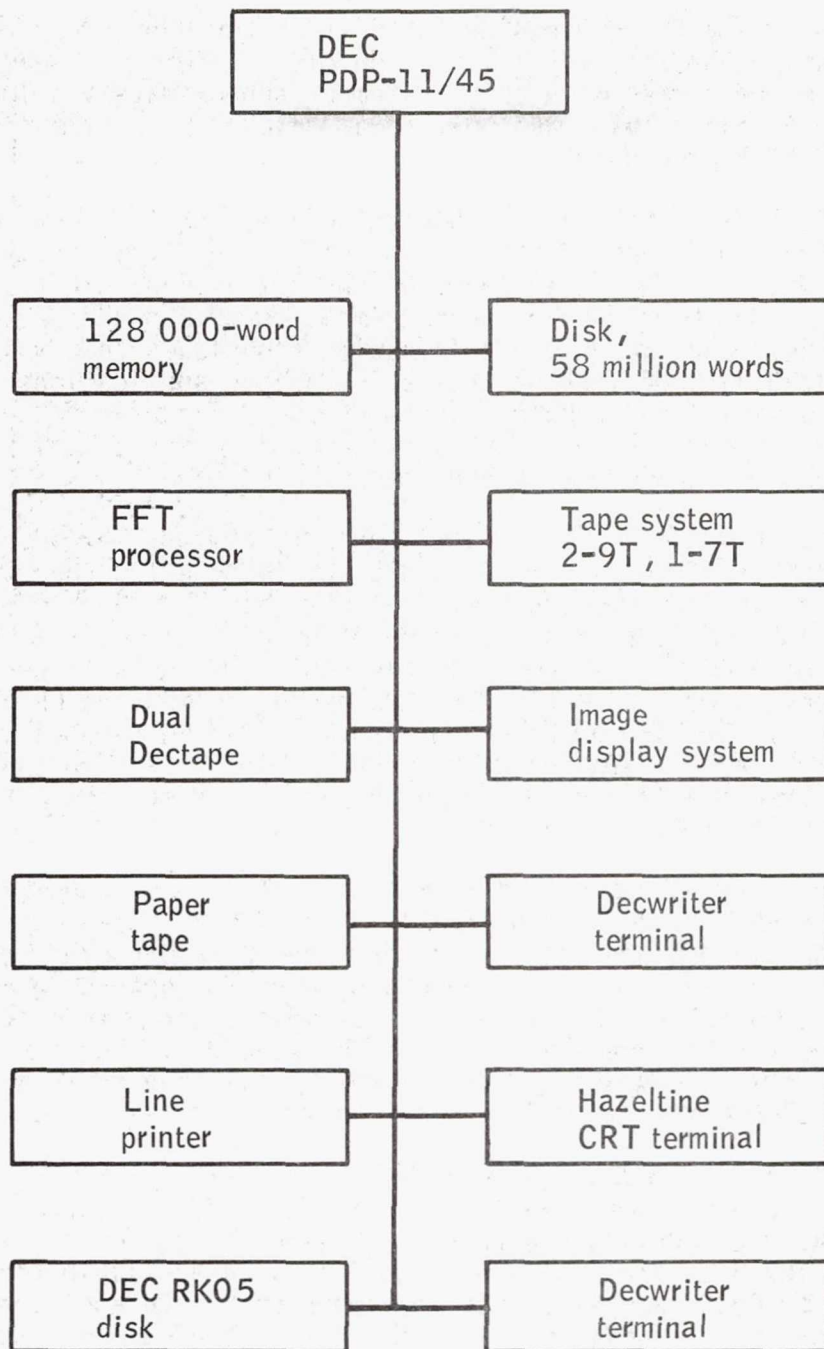


Figure 5-20.- Facility for digital radar data processing and exploitation.

outlines or annotation data can be superimposed on the displayed images without destroying the contents of the display memory. In addition, a trackball-controlled cursor allows the user to extract positional information from the displayed images. A diagram of the interactive display system is shown in figure 5-21.

Additional features of the display are the programmable table-lookup memories installed between the display memory and digital-to-analog (D/A) converters that provide the video intensities. Under program control, these memories can be loaded with intensity transfer functions that are then applied to the images on a point-by-point basis in real time as they are displayed. The transfer function can be constructed to provide contrast enhancement, thresholding, image intensity inversion, pseudocolor encoding, or any of a number of single-point image manipulations, the results of which are nearly instantaneously visible to the operator. The display is used to view digitally processed SAR imagery and to examine image exploitation techniques.

SAR digital processing consists primarily of the application of two-dimensional pulse compression techniques to digital signal histories. The digital facility serves as a general-purpose tool for examining such techniques. The two-dimensional pulse compression is generally implemented as two one-dimensional digital matched-filtering operations in conjunction with range and azimuth prefiltering operations analogous to the frequency plane filtering used in the optical processing technique previously described. The FFT hardware is useful for performing the various types of digital filtering operations. The digital facility has been structured for highly controlled experimental processing rather than for emphasizing real-time applications.

The facility has proven extremely valuable in SAR digital processing and simulation efforts. Data inputs that have been used to date include digitized versions of optically recorded phase histories, as well as purely digital phase histories obtained from both a ground-based SAR simulation system and from digitally recorded airborne phase histories. Several types of SAR data have been processed into imagery and subjected to digital image exploitation efforts.

The Westinghouse Corporation has the capability to process SAR data in its Interactive Processing Facility. This capability was designed to be very flexible to prove the application of various processing algorithms and the interaction of a human operator with the processing of the radar data. The facility is built around three Data General general-purpose computers: a Nova 800, a Nova 840, and an Eclipse S-200. The FFT operations involved in the data processing are accomplished with a hard-wired ELSYTEC FFT board in the Nova 840 to improve the processing rate. The bulk memory is in the form of four disk units. The peripheral equipment includes 315.0- and 629.9-bit/cm (800 and 1600 bit/in) tape units, CRT and teletype terminals, line printers, a film hard-copy unit, and a color CRT display for interactive processing.

The Applied Research Laboratory (ARL) of the University of Texas at Austin (UT) has an extensive background in SAR data processing, dating from 1968 and its involvement in the Air Force's FLAMR program as the

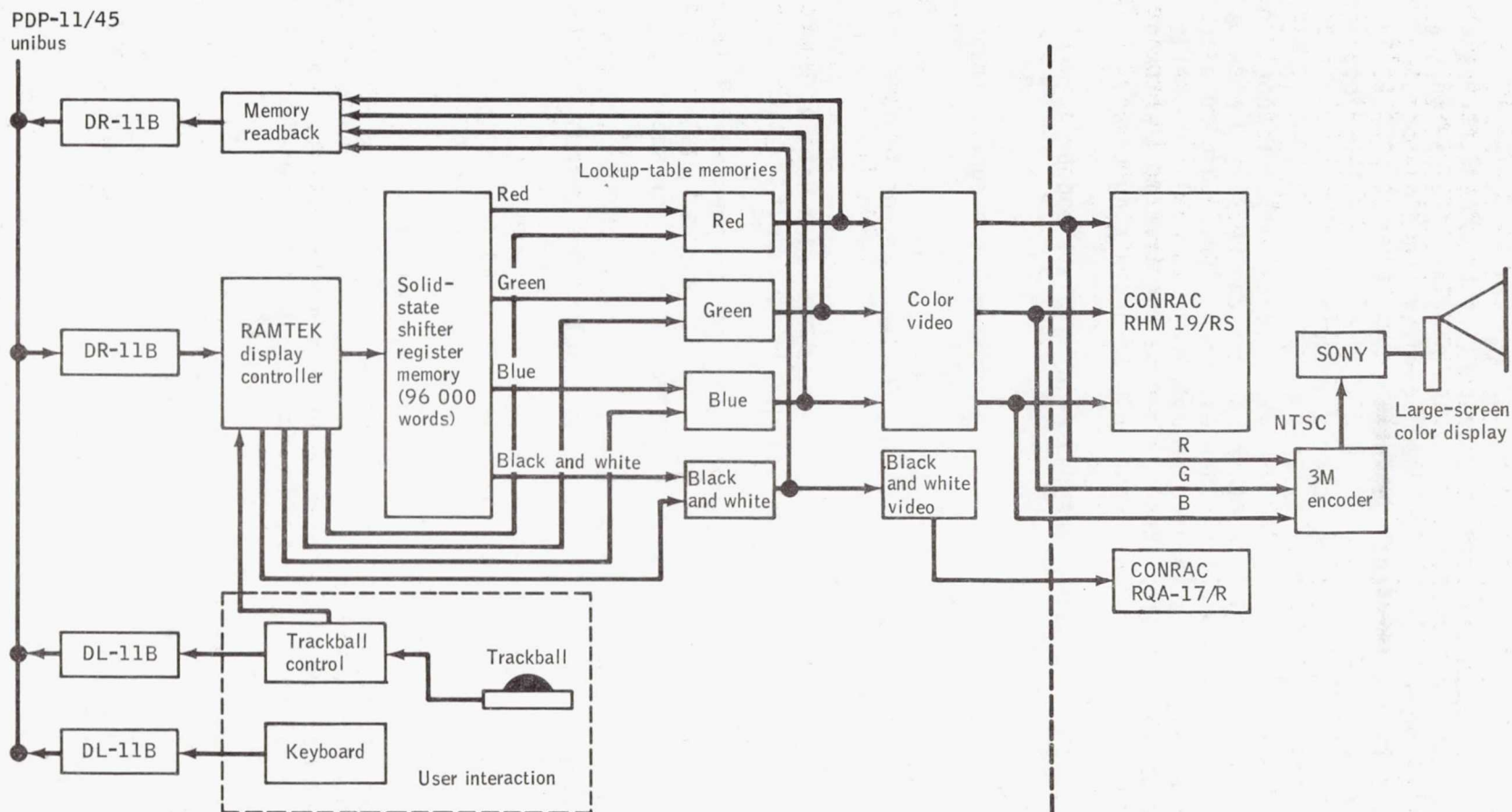


Figure 5-21.- RAMTEK digital image display block diagram.

data analysis contractor. The FLAMR system was the first real-time digitally processed SAR system flown. In support of the FLAMR, the ARL developed a large number of SAR-data-processing programs for use on the ARL twin Control Data Corporation (CDC) 3200 computers and on the UT CDC 6600 computer. The ARL presently maintains the FLAMR data bank, containing over 400 wide-band magnetic tapes of digital SAR I/Q video and auxiliary data from which SAR imagery can be produced.

Figure 5-22 shows the ARL SAR data analysis capability. Either FLAMR data or properly formatted data from other sources can be played back by using the FLAMR digital recorder interface equipment (DRIE) ground playback system. The DRIE allows the conversion of data from wide-band magnetic tape to CCT form for subsequent processing. Programs have been written to perform the following SAR image formation data-processing tasks.

1. Validating the raw SAR data and providing plots and printouts as required
2. Reformatting the data to allow more efficient subsequent image-formation processing
3. Performing range compression of the FLAMR binary phase coded waveform
4. Applying motion compensation to the raw I/Q video data with the use of information from the FLAMR inertial measurement unit
5. Performing azimuth compression of the range-compressed SAR video
6. Postprocessing the raw filter magnitude data by thresholding and assigning gray shades
7. Determining the statistics and image quality for processed SAR data

Other special software has been written to fulfill the following functions.

1. Degrading the imagery signal-to-noise ratio by the addition of band-limited noise to unprocessed SAR I/Q video data
2. Degrading the SAR I/Q video data precision to simulate data quantized with lesser precision to allow the investigation of the effects of data precision on image quality
3. Performing trade-off studies by varying the resolution, sampling interval, and overlay of processed imagery
4. Producing high-quality composite images on the ARL precision display for use in image interpretability studies

The ARL is also developing for NASA a general mathematical model of the SAR processes that will enable the generation of simulated I/Q video from complex scenes that can be processed to form SAR images of such scenes.

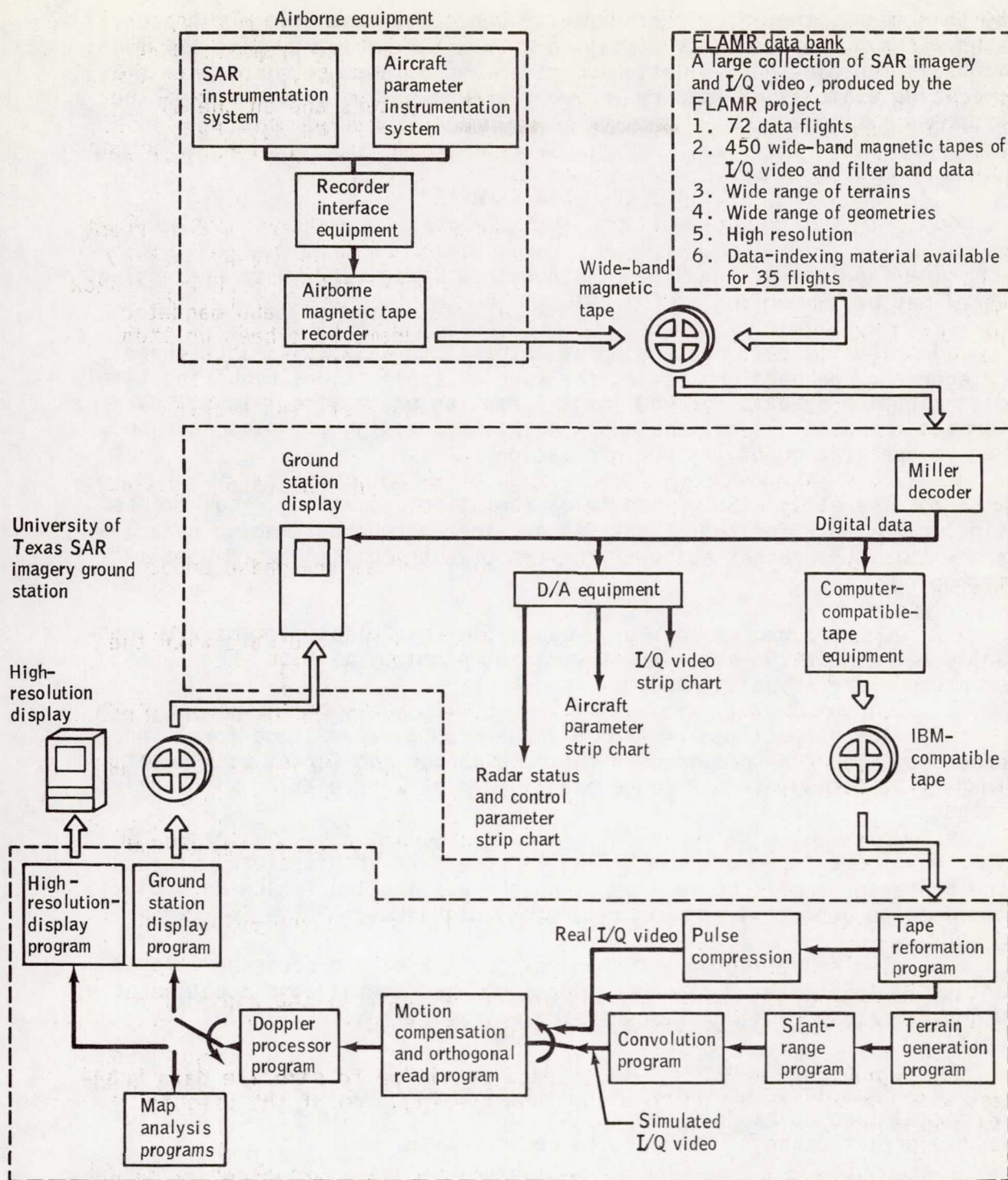


Figure 5-22.- The University of Texas (ARL) digital SAR processing capability.

By this means, the effects of geometry-dependent distortions can be evaluated without the necessity of flying actual SAR hardware. The ARL model will also enable the evaluation of radar and data-processing systems by producing examples of imagery formed with use of the parameters of the proposed systems.

CONCLUDING REMARKS

The findings of the Synthetic Aperture Radar (SAR) Data Processing Panel may be summarized as follows.

1. The SAR data processing of interest to NASA falls into three categories: onboard processing for special applications requiring timely dissemination of data, ground image formation processing into standard formats for general applications, and postprocessing of image data to derive specific quantitative information.

2. The early NASA ground image formation processing requirements (including those for the Seasat SAR and the spaceborne imaging radar) are within the present state-of-the-art of both optical and digital technology.

3. Onboard processors for L-band 25-m-resolution systems are presently not within the state-of-the-art but probably will be when such processors are actually needed.

4. The output imagery from a large ground-based image formation processor should be provided in the same manner and format as Landsat imagery to facilitate SAR image acquisition and correlation with optical imagery.

5. There is no optimum SAR-data-processing architecture, because the processor architecture depends on the application (which determines the imaging geometry) and the technology utilized.

6. The selection of a technology for SAR data processing is presently driven by memory considerations, not arithmetic considerations. Other important considerations are power, weight, size, flexibility, and cost.

7. In a large ground-based SAR-data-processing facility, some form of a real-time quick-look processing capability should be provided to enable prescreening of the data to be processed.

The panel recommendations are as follows.

1. An Imaging Radar Technology Group should be established by NASA to develop and maintain technical expertise applicable to current and proposed NASA imaging radar systems. This group should meet at least once a year.

2. NASA should support an imaging-radar-technology study program to conduct investigations related to gathering, processing, and disseminating imaging radar data. Study areas that should be supported are as follows.

a. Requirements for antenna pointing and motion compensation for satellite-borne SAR systems

b. Requirements and processing implications for squint-mode SAR operation

c. Interpretability-versus-image-parameter trade-offs for digital SAR imagery

d. SAR calibration techniques

e. The interface between a SAR image formation facility and the users

3. A central SAR image formation processing facility should be established by NASA to provide users with cataloged SAR data in standard formats.

4. The development of onboard processors for dedicated applications requiring timely dissemination of image data should be pursued.

5. Existing airborne SAR measurement facilities should be modified to include the recording of raw sensor data in digital form.

6. Raw aircraft and Seasat data should be made available to support the recommended imaging-radar-technology study program.

7. The development of high-density data storage devices such as the RCA 240-megabit/sec magnetic tape recorder should be continued.

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